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Optimal Planning and Operation of CHP in Multi-Carrier Energy System

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Optimal Planning and Operation of CHP in Multi-Carrier Energy System

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Contents

Abstract

In the development of the energy industry, environmental impact, particularly carbon emission has always been a great challenge. Combined heat and power (CHP), as a highly efficient method to simultaneously generate both electricity and heating, is playing a crucial role in the power industry, which possesses the following features: 1) it uses cleaner energy source such as natural gas, biomass compared to traditional fossil-fuelled power plants; 2) it could significantly reduce carbon emissions by capturing the heat produced as a by-product. The trend of interconnecting various energy vector infrastructures and energy services requires more energy conversion technologies. The multi-carrier energy system is thus introduced to allow the interactions of different energy carriers, enabled by energy conversion and storage technologies.CHP is playing an important role as a coupler for multi-carrier energy system. The optimal CHP planning and operation in multi-carrier energy system has become a hot topic. There are two main aspects: one is the combined model of multiple-carrier energy flows, which should be formulated and the other is to find suitable CHP planning and operation schemes. A vast number of optimal CHP planning and operation methodologies have been proposed. Most of them are motivated by energy savings. However, they are limited to the economic contribution of CHP while ignoring its wider impact on multi-carrier energy systems.

Therefore, this thesis has carried out an intensive research on optimal CHP planning and operation, and then analysed the impact on multi-carrier energy system investment and energy costs. The major contributions are summarised as follows:

- Investigate the correlation between gas and temperature to obtain the gas load characteristics for the further CHP planning and operation.
- Propose an optimal CHP planning method considering the future investment from the perspective of the electricity network operator.
- Extend and improve the proposed CHP planning method in a multi-carrier energy system with both gas and electricity network considering the future network.
- Propose a multi-objective optimal CHP operation model cooperated with an energy hub (EH) system considering the investment cost (InC), energy cost and carbon emission cost.

These proposed methodologies are demonstrated on the practical distribution system in different scenarios with sensitivity analysis and the results are proven to be effective and applicable. The optimal CHP planning considers the impact of the CHP on the multi-carrier energy systems and benefit system operators with reduced InCs with CHP's installation. The short term optimal CHP operation benefits local network owners with reduced energy cost and carbon cost savings compared to traditional generation.

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List of Abbreviations

AF	Annuity Factor
AV	Asset value
B	Susceptance
CC	Carbon cost
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined heat and power
CoP	Coefficient of Performance
DECC	Department of Energy & Climate Change
DER	Distributed energy resource
DG	Distributed generation
DH	District heating
DR	Discount Rate
DUKES	Digest of UK Energy Statistics
EC	Energy cost
EH	Energy Hub
EMD	Empirical Mode Decomposition
G	Conductance
GDN	Gas distribution network
GHG	Greenhouse Gas
GR	Growth Rate
HES	Hybrid energy storage

HP	Heat pump
HtER	Heat to electricity ratio
IC	Incremental cost
IMF	Intrinsic mode functions
InC	Investment cost
LRIC	Long-run incremental cost
LS	Life span
M-distance	Mahalanobis distance
MILP	Mixed integer linear programming
NC	Normal cost
PV	Photovoltaics
p.u.	Per unit
R	Resistance
RE	Renewable energy
RHD	Reinforcement horizon deferral
UC	Utilisation change
UoS	Use-of-system
X	Reactance

Chapter 1.

Introduction

THIS chapter briefly introduces the background, challenges, motivation, objectives and contribution of this research project. It also provides the outline of this thesis.

1.1. Background

1.1.1. Decarbonisation in the Energy Industry

Carbon emission is one of the most challenging problems to tackle in the energy industries. Traditional energy production process emitted a large volume of carbon dioxide which raised a huge impact on the overall greenhouse effect. In 2009, annual energy-related carbon emission of the top ten countries was accounted for about 2/3 of the world's total carbon emissions, as shown in Figure 1-1 [1]. The total carbon dioxide CO_2 emission on worldwide was 30,313 million metric tonnes. China contributed the most CO_2 emission in 2009 in the figure, accounting for 23.6% of the global value, followed by the United States of 17.9%. The United Kingdom was the tenth country for the most carbon emission, which was accounted for 1.6% of the globe.

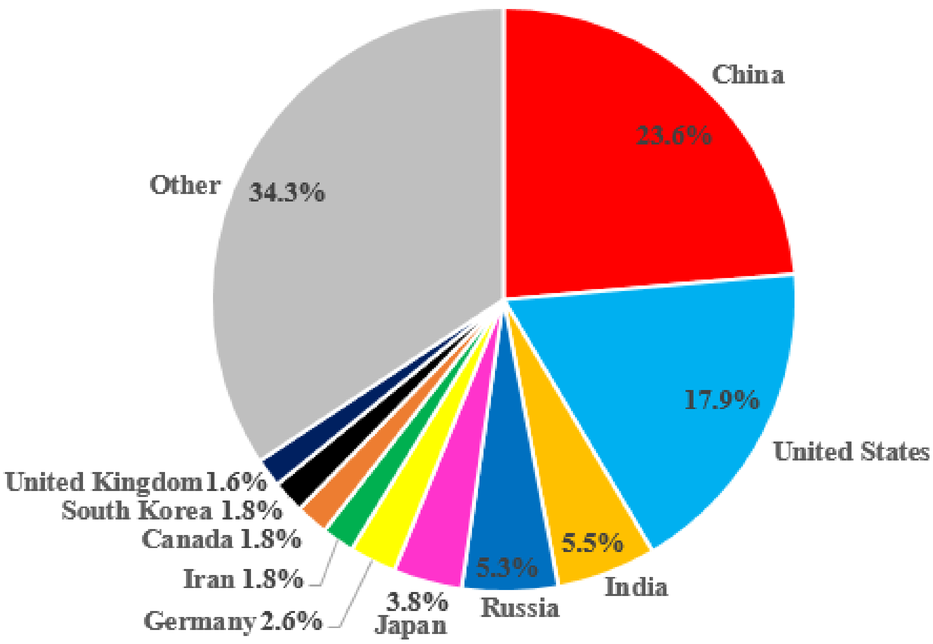

Figure 1-1. Pie Chart of Global Carbon Emission by Countries of 2009[1]

Another annual cumulative energy-related carbon emissions by countries from 1850 to 2008 in [1] showed that the UK was ranked sixth in the top 10 cumulative carbon emission countries, which was 5.73% of the world in total. The carbon emission per person was ranked second with 1127.8 metric tonnes of CO_2 per person, only after the United States.

Since the later 1980s, governments around the globes had made regulations and rules to encourage energy industries to improve the efficiency and reduce the carbon emission, starting from Chile, then England & Wales, and to many other countries around the world [2].

After the year 2000, international negotiations and national targets tried to reduce the carbon emission significantly to reduce the risks of global warming. Regulations and Acts were taken action to the decarbonisation progress in power industries. In the UK, the Climate Change Act was legislated in 2008 to ensure that the UK net carbon emission by the year 2050 is at least 80% lower than the 1990 baseline. More detailed carbon budgets are placed every five years to set a restriction on the total greenhouse gases (GHG) in the UK, which makes the UK the first country to set legally binding carbon budgets. The fourth budget from 2023 to 2027 period will be 1,950 million tonnes of CO_2 equivalent, which is 50% lower than the 1990 baseline.

The electricity sector is playing an important role in meeting these targets. The traditional carbon footprints of fossil-fuel electricity generation are shown in Figure 1-2.

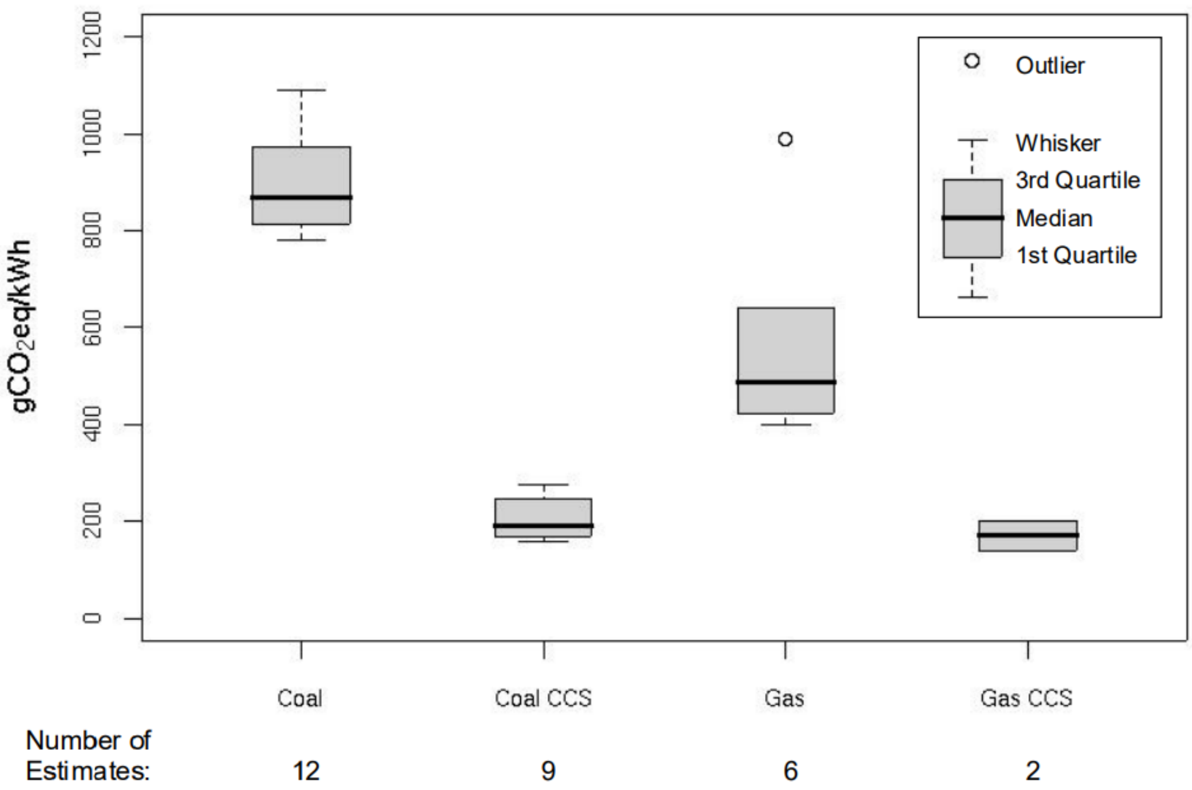

Figure 1-2. Traditional Fossil-Fuel Electricity Carbon Footprints[3]

Carbon capture and storage (CCS) technology [4] is a process to relatively reduce the carbon emission during the electricity generation, compared to traditional generation. The traditional coal fuelled electricity generation is with a higher of carbon emission. In fact, with the development of electricity generation technology, the average emission is dropped from 718 gCO_2eq/kWh in 1990 to 500 gCO_2eq/kWh in 2008 [3].

Heating used for domestic, commercial and industrial purposes accounts for around a third of its GHG emissions in the UK [5, 6]. Among these emissions, 50% of them are from the domestic sector, and 20% are from the commercial sector. For these two sectors, space and water heating are responsible for 98% of the emissions, and cooking is responsible for 2%. The last 30% of emissions are from the industrial sector, of which specialised industrial processes account for 87% and space and water heating only accounts for 13%. Traditional heating technology is fossil-fuelled boilers, for example, oil boilers, which accounts for 88% of the domestic heating and has a relatively high carbon footprint compared to newly developed technologies such as CHP and heat pump (HP) *etc*. The carbon footprints of all heating technologies are shown in Table 1-1. The change of carbon footprint of boilers and HPs is according to their technologies, lower carbon footprint comes with higher capital cost. These two means could only convert single energy source into heating while CHP could realise three types of energy conversion between gas, electricity and heating.

Table 1-1. Carbon Footprint of Heating Technologies[5]

Technology	Carbon Footprint (gCO_2eq/kWh)
Oil Boilers	310-550
Gas Boilers	210-380
Electric Heaters	370
CHP	220
Gas Absorption Heat Pump	150-200
Ground Source Heat Pump	70-190
Air Source Heat Pump	90-250

Though the progress on decarbonisation has been done in the energy sector over the last decades, criticism still is made that this progress is still too slow. Following this criticism, the UK government has taken more actions towards the goals of decarbonisation set by the Climate Change Act.

1.1.2. CHP in the Decarbonisation

Combined Heat and Power integrates the production of usable heat and electricity in a single, highly efficient process, shown in Figure 1-3. During the process of electricity generation of CHP, the by-product waste exhaust is captured and recycled for heating purpose. Compared with separated means of traditional energy generations such as power plate and heat boiler, CHP could reduce carbon emission by up to 30%.

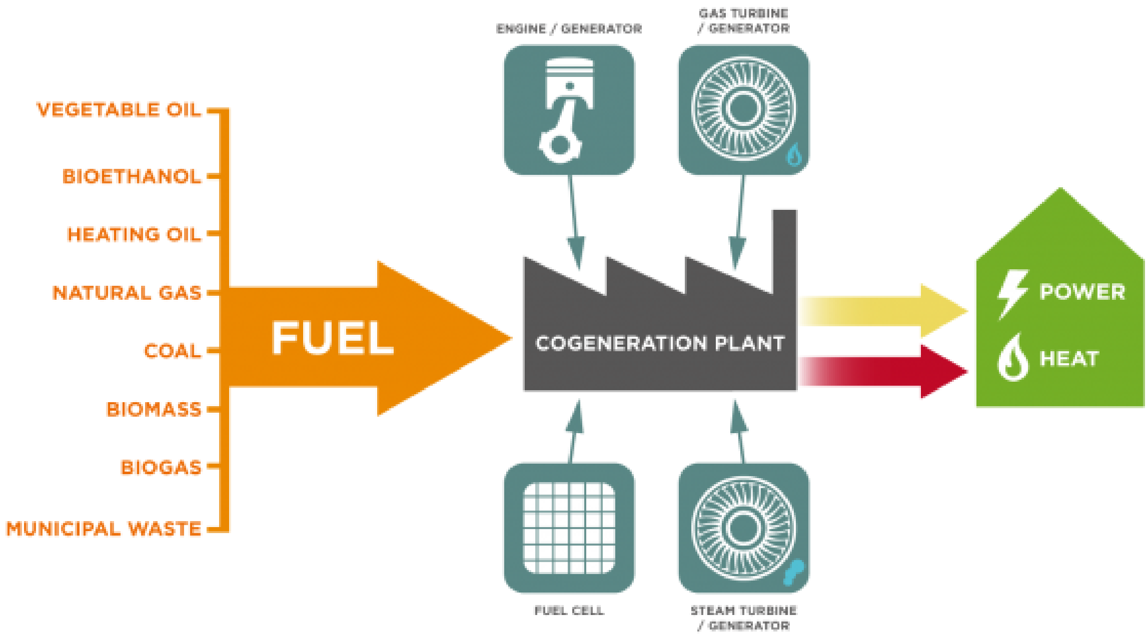

Figure 1-3. The Principle of CHP[7]

Despite the improvement of environmental performance, CHP is also highly efficient during the energy production as it captures and utilises the heat with an overall efficiency of over 80%, whilst efficiency of most gas-fuelled power stations in the UK ranges between 49% to 52% and coal-fuelled power station with a lower efficiency of around 38%. Operators could also benefit from the CHP with a reduced energy bill of around 20% lower compared with conventional energy[7]. As the most significant single opportunity to reduce energy cost and carbon emission with high efficiency, CHP is functioned as an important mean to participate in decentralised energy. Additionally, CHP also helps losses reduction incurred through transmission and distribution and increase fuel supply security as an on-site generation. In the UK, 7% of energy is lost in the transport network through the transmission network and the local distribution networks from the generation side to the customer side.

European Commission has developed a Directive in 2004, aimed at promoting CHP in the internal energy market and improve the security of supply energy [8]. It is intended to be achieved by creating a framework for the use and development of CHP with high efficiency. Member states should be obliged to this act to produce reports on their implementation and development of high-efficiency CHP.

In the UK, the government has committed to developing CHP with incentive acts. CHP Focus is a Department of Energy & Climate Change (DECC) initiative to support the development of CHP, which guides CHP developers to find comprehensive information on all aspects of CHP in terms of technologies, development and assessment. The Combined Heat and Power Developers Guides published in 2008 [9] provided full details of CHP employments including project development, technologies, finance, environmental, operation and maintenance. DECC opens handle tools for the public to access the information of CHP development. For example, CHP Site Assessment tool [10] allows users to obtain an indicative assessment and get potential options to install CHP on a particular site, CHP Development Map [11] allows users to find out heat demand across various sectors in the UK geographically and CHP Scheme Database [12] allows the public to obtain detailed information such as the site name, capacity, industry sector, region and prime mover of in-operation CHP in the UK.

With the further penetration and rapid development of CHP, in 1997, CHP was firstly added as a separate chapter in the Digest of UK Energy Statistics (DUKES), known as an essential source of national energy information published by the UK government [13]. The increasing utilisation of CHP in the last 20 years in the UK are shown in Figure 1-4.

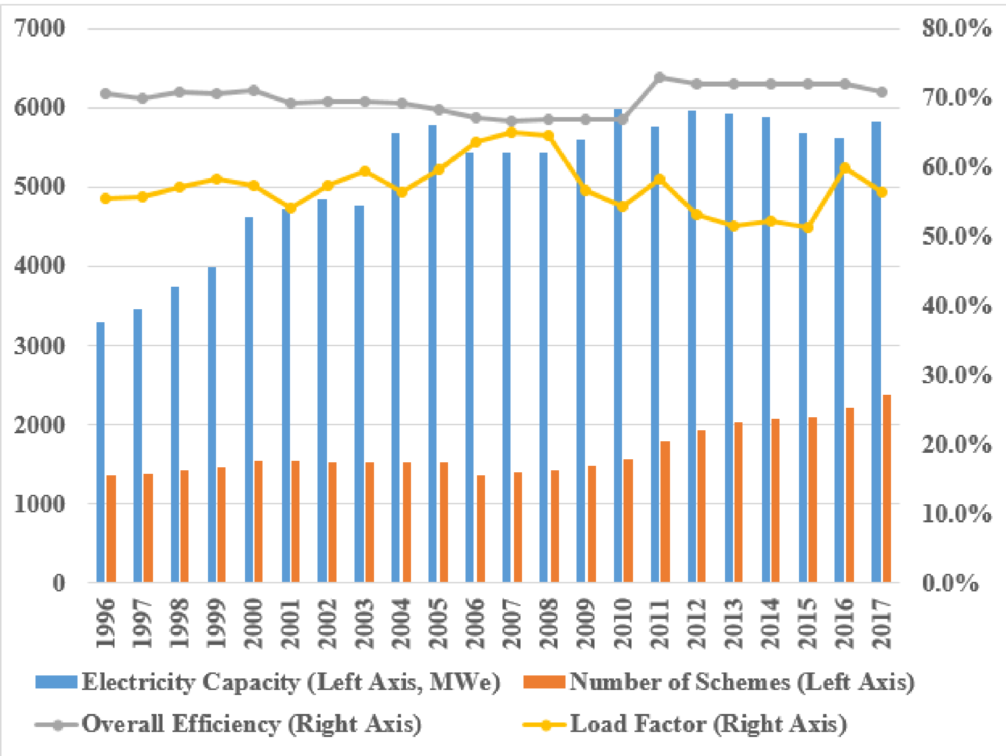

Figure 1-4. CHP Development from 1996 to 2017 in the UK[13]

In the past two decades, the overall efficiency of the CHP schemes operated in the UK was around 70% and the amount of operational time for CHP scheme is at around 60% annually. The number of CHP schemes added is from 1370 in 1996 to 2386 in 2017. This indicates a 74% growth in numbers in the past two decades. Electricity capacity increased by 77% from 3301 MWe in 1996 to 5885MWe in 2017. In 2017, the total electricity capacity was 5885 MWe, increased from 5625 MWe in 2016, which generated 21.6 TWh electricity, accounted for 6.4% of the total annual electricity generation in the UK. As for the heating, the heat capacity was 20191 MWth and generated 42.2 TWh heat in 2017. Furthermore, from the last five year's DUKES, it could be known that CHP has grown steadily in the UK. Hence with the increasing growth and promising future of on-site CHPs, it will have a significant impact on both the electricity network and natural gas network and its planning appears to be vital in the multi-carrier energy system.

As mentioned in previous, the UK government encourage the development of CHP with several incentive policies. CHP is set to develop with lower carbon footprint and high efficiency. Its development is an important part in setting a clearer course to the 2050 climate change target. Therefore, it is necessary to study the impact of CHP's penetration in the energy market and make optimal planning for CHP installation to maximise its benefit and counter the drawbacks from traditional low-efficient generations.

To summarise, CHP plays in a crucial role in the decarbonisation transition, due to its advantages of capturing heat from the electricity generation and using it to supply local heat demand. Compared with traditional generation methods like electric power station and heat boiler, CHP is able to reduce carbon emission by up to 30%. To this end, the UK government has initiated several incentive policies by providing CHP users with guidance, information and tax exemption to support the development of CHP schemes. In the last two decades, CHP has increased by 74% in number of schemes and 77% in capacity. Hence, following the trend of CHP development, more CHP schemes will participate in the market in the future.

1.1.3. CHP in Multi-Carrier Energy System

Traditionally, the infrastructure of the supply of electricity, natural gas and heating energy has been managed in an independent manner. However, with the rapid development of energy conversion components between different energy carriers, an increasing mutual coupling and interaction have been established between these energy infrastructures. The multi-carrier energy system is introduced to represent a system with different energy flows and have interdependencies enabled by different technologies of energy conversion. Multi-carrier energy system exists in both large and small energy systems, on transmission level as well as distribution level. In recent years, the fast development of multi-carrier energy system is particularly driven by the increasing penetration and development of the energy conversion and storage technologies such as CHPs, DGs and REs [14]. Due to the ability to interconnect gas network, electricity network and heating network in a highly efficient manner, the popularity of CHP is rising in aggregating multi-carrier energies in recent years.

In multi-carrier energy system, there are two main focuses compared with traditional single energy vector network. The first part is the energy flow modelling of each of the energy vector within the multi-carrier energy system. The second part is the proper formulation of the energy conversion or energy storage technologies to enable interaction between different energy vectors.

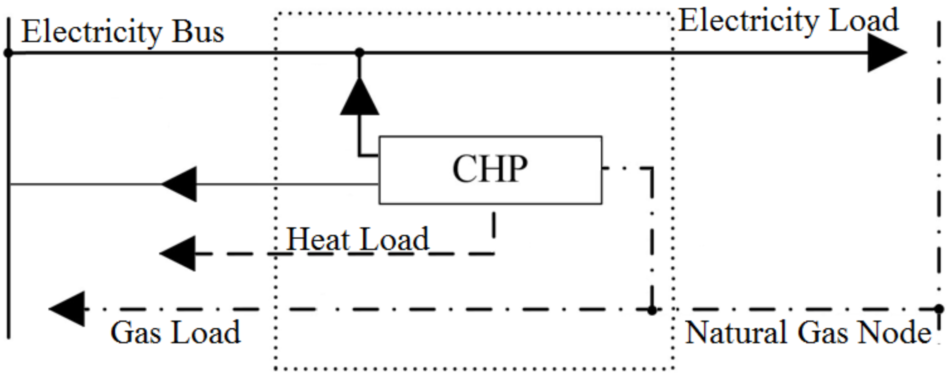

Figure 1-5. Power Delivery of a Gas-Fired CHP in a Multi-Carrier Energy System

As CHP is playing as an important coupler in the multi-carrier energy system, the studies on the optimal CHP planning and operation have become popular in recent years. As indicated in Figure 1-5, a gas-fired CHP can deliver power in a multi-carrier energy system. In the figure, CHP is fuelled by gas to produce electricity and heat simultaneously, the heat is delivered locally to support space/water heating while the electricity supports the local electricity demand. If the electricity demand is met, excess electricity could be sold back to the electricity network. Hence, a CHP system has the ability to interconnect three energy vectors by converting natural gas into electricity and heating. The implementation of high efficient CHP system could alleviate the reliability on the grid as well as reduce the carbon emission and energy cost.

1.2. Challenges

With the improving technology of CHP and rapid penetration of CHP into the multi-carrier energy system, the employment of such energy conversion technology in multi-carrier energy system would cause severe challenges to the security and reliability of the system.

1.2.1. Different Energy Flows Conversion

Unlike separate energy networks that only have to consider a single type of energy source, in a multi-carrier energy system, different types of energy sources should be carefully modelled [15]. The power flows in different energy carriers are challenging to model especially when different types of energy converter make the interaction between them considering different energy characteristics. Proper energy formulations and energy conversion modelling are the breakthrough point in the study of the multi-carrier energy system.

1.2.2. Planning CHP with Novel Models

The high deployment of CHPs in the multi-carrier energy system, in fact, requires more system transportation capacities in different networks. Yet most CHP planning research is focusing on the CHP capital cost, energy bill reduction and carbon emission reduction [16]. It is difficult to quantify how such CHP employment would impact the building of excess power capacities in both the electricity network and natural gas network. Such investment needs to be justified based on the redirected energy flows and the future upgrades of the multi-carrier energy system.

1.2.3. Optimal Site and Size of CHP

Many influences should be assessed in planning CHP, not only considering CHP as an enabler to interact with both electricity network and natural gas networks, but also the feasibility of such planning [17]. There are limited locations and capacities might be available for selection in practical networks. Therefore in the planning schemes,, CHP, as coupling equipment, should be planned considering practical geographically feasibility.

1.2.4. Advanced Operation of CHP and Other Energy Technologies

The traditional research on energy equipment operation were designed for independent energy networks. Therefore only a single energy network formulation is considered, and the optimisation progress is mathematically easier to perform with fewer input variables and simpler network modelling compared with that in the multi-carrier energy system [18]. However, with the consideration of multiple energy vectors and energy services provided by energy conversion and storage technologies, more models and constraints are introduced into the formulation. Not only CHP, but also other equipment such as photovoltaics (PV) and HP might be introduced to interconnect different energy carriers. Therefore, proper modelling of different energy technologies is required to tackle such an optimisation problem.

1.3. Research Gaps

With the growing CHP technologies and its penetration into the multi-carrier energy system, problems might occur during this progress, such as their increasing impact to the network planning and operations. Hence, this research is motivated to deal with the following problems.

1.3.1. New Formulation of Multi-carrier Energy System

As there are several energy vectors in a multi-carrier energy system, the traditional method of modelling the independent electricity network or natural gas network may not be suitable in multi-carrier energy system modelling. New methodologies of formulating this multi-carrier energy system are required to investigate the influence of CHP employment.

1.3.2. Unable to Reflect the Network Utilisation

As previously mentioned, most optimal CHP planning studies, either in single electricity network or in the multi-carrier energy system, only reveal the influence of CHP on the energy cost, environmental impact or energy bill savings in the short term. Very limited research tried to evaluate the influence of CHP on the network flows and network transmission utilisation for both electricity network and natural gas network in the long term. In fact, this is important information for the network operators to make plans for future reinforcement. As CHP employment into the multi-carrier energy system will cause injection in different energy networks, such injection could also bring forward or delay to the investment horizon of network components.

1.3.3. Ignoring Load Characteristics in CHP Operations

CHP optimal operation in multi-carrier energy system is very sensitive to the energy loads to achieve a certain goal as well as satisfy the load demand. Yet existing operation strategies are generally conducted with the load variation represented by a load growth rate. Such a linear representation of the load could not reflect the substantial characteristics of the load change.

Therefore models to factually represent load characteristics are required to improve the accuracy and performance of CHP optimisation.

1.4. Research Objectives and Contributions

In this thesis, an optimal CHP planning method considering the future network investment is proposed firstly in the electricity network, and then applied to the multi-carrier energy system. Thereafter, the optimal operation of CHP with an EH system in a local multi-carrier energy system is studied to justify the benefits. The main objectives and contributions are outlined as:

1.4.1. Identify the Characteristics and Model Electricity and Natural gas Load

As the proper planning and operation of CHP depend on the load such as electricity and gas, it is essential to identify the load characteristics and model the load profile properly. The conventional CHP planning and operation methods were proposed based either on fixed demand or fixed load growth rate, the results therefore, could not veritably reflect the load change.

To do so, the analysis to study gas load characteristic is conducted by identifying its correlation with temperature. The results indicate the temperature has a profound impact on gas demand which could be used for gas load modelling. With the existing adequate studies for electricity load modelling, it could provide a theoretical basis for the load prediction for both electricity and gas which would be further used in multi-carrier energy system to obtain accurate CHP planning and operation optimisation.

1.4.2. Propose a Novel CHP Planning Method Reflecting Network Investment

Most CHP planning optimisation research is focusing on energy savings, carbon emission reduction or a trade-off objective. This thesis addresses the planning problem from another aspect to investigate the influence of the energy injection brought by CHP on the network utilisation, advancing or deferring the future network reinforcement horizon.

To do so, the concept of long-run incremental cost (LRIC) [19] and network charges are introduced. The optimal planning of CHP in a multi-carrier energy system could be divided into two parts. Firstly, an LRIC matrix is proposed to determine the optimal site of CHP.

Secondly, an objective to minimise the future network reinforcement is proposed to determine the optimal size of CHP. This proposed method is firstly implemented on an electricity network, which proves its effectiveness. Then it is implemented on an integrated network consist of both electricity and natural gas.

1.4.3. Extend Concept of LRIC to Natural Gas Network

The idea of LRIC is redesigned for natural gas network charges by using the gas flow injection into network pipelines to determine the impact of demand/generation on the present value of network reinforcement cost. This impact of gas flow change caused by the CHP could be quantified by using this as an economic signal.

To do so, the difference of the principle and mechanism in terms of future investment between electricity network and natural gas network should be understood thoroughly. For electricity network, when power flow on a line reaches its maximum capacity, network reinforcement will be taken place by adding another parallel line to meet the growing electricity flow. For the natural gas network, additional compressor station is required as a reinforcement measure to meet the growing gas flow. The measures of future investment of electricity and gas network are different, therefore, a model to calculate LRIC in the natural gas system is adjusted considering future gas branch reinforcement.

1.4.4. Design Optimal Operation of CHP in Multi-carrier Energy System

Planning and operation are two important aspects of CHP implementation in the multi-carrier energy system. Therefore, it is also crucial to determine the CHP operation to meet real-time demand. This includes how CHP supply both electricity and heating load during a long period of time with changing load as well as its performance in saving energy bills.

To do so, an optimal operation with multi-objectives for CHP in an EH is proposed and tested on a local multi-carrier energy system. Different case studies are carried out to show network InCs recovery, energy cost and carbon cost savings and carbon emission reduction achieved by applying the proposed method.

1.5. Thesis Outline

The rest of the thesis is organised as follows:

Chapter 2 briefly introduces the multi-carrier energy system and CHP. The first half explains what is a multi-carrier energy system including a comprehensive review of the system from four perspectives. The planning and current planning criterion for multi-carrier energy system are also introduced. Afterwards, a comprehensive literature review of CHP is provided, which includes policies and acts made on CHP, CHP operating principle, CHP modelling, CHP planning and operations.

Chapter 3 identifies the correlation between temperature and gas load in a local energy system. Use data mining technique to detect outliers from the data set then apply data processing techniques called Empirical Mode Decomposition (EMD) to identify the relationship between temperature and gas load. The results show that a high level of correlation between the gas load and the temperature could be identified using with original data.

Chapter 4 proposes a method to optimally plan CHP considering network investment. A novel method to identify optimal CHP location using LRIC matrix is applied in the test system. Then minimised total incremental cost (IC) of the electricity network lines is used as the objective to determine the optimal size of CHP. This proposed method is implemented on a 15-bus distribution network. It provides the reader with a planning method from another novel aspect by looking into the benefits of future InC rather than focusing on energy cost or environmental impact.

Chapter 5 applies the proposed method in Chapter 4 in the multi-carrier energy system composed of both gas and electricity network. The gas network is formulated and an LRIC matrix in the natural gas system is proposed by adding compressor station as future reinforcement rather than adding a transmission line in the electricity network. With the use of CHP as an enabler to interact between two energy systems, a total LRIC matrix from both networks to select the optimal site for CHP is presented. A 15 bus, 12 node distribution multi-carrier energy system is tested to demonstrate the effectiveness and applicability of the proposed method to actual systems.

Chapter 6 presents a multi-objective optimisation process to determine the optimal operation of CHP and EH according to InC, energy cost and carbon emission in a local energy system. The optimisation problem is formulated on the coupling electricity gas and heating load. The results show a set of optimal solution of each component of the CHP and EH system including their half-hourly operation and the trade-off between them in order to achieve multi-objectives.

Chapter 7 summarise the key findings and main contributions of this research and provides some potential research in CHP planning and operation in a multi-carrier energy system in the future.

Chapter 2.

An Overview of Multi-Carrier Energy System and CHP

THIS chapter introduces the concept of multi-carrier energy system and CHP. The first half gives a review on different energy flows and planning in multi-carrier energy system. The second half introduces the modelling, planning and impacts of CHP.

2.1. What is Multi-Carrier Energy System

Traditionally, energy sectors have been de-coupled from each other in terms of planning and operations. With the rapid development and increasing penetration of on-site distributed generation (DG) with different energy fuels, especially CHP, the interdependency between different energy carriers is becoming closer. Thus the concept of the multi-carrier energy system is introduced to represent energy system contains a different type of energy sources and the energy conversions between them, which establishes a coupling of the corresponding energy flows resulting in system interactions [20].

Multi-carrier energy system could also be referred as an integrated energy system, whereby electricity, natural gas, other fuels, heating/cooling, transport and so on interact with each other at different levels to develop toward a cleaner and affordable energy system. The size of this system could vary from within a building, a district, up to a city or a country. The development of the smart grid and the increasing deployment of DG are examples of implementation of the multi-carrier energy system. Compared with conventional independent or separated energy system, multi-carrier energy system could provide a better technical, economic and environmental performance of both planning and operation stages[21].

The term 'multi-carrier' or 'integrated' indicates that multiple energy vectors and sectors are integrated, not only supply and demand side, but also the energy flows, transport and energy conversion between each other. The purpose of putting forward the multi-carrier energy system or integrated energy system is to consider the optimisation or evaluation of the different energy network as a whole under specific cases. Therefore, using this framework to study and analyse has expanded to explore the interest of the whole system and break the boundary beyond separate energy systems such as only considering electricity or only considering heating like traditional energy network cases.

By doing so, using the concept of the multi-carrier energy system in the study could play a key role in bringing the following benefits:

- It introduces more energy converters into the system, improve the conversion efficiency, and increase the utilisation of energy sources such as DG and renewable energy (RE);
- Provide suitable condition for the development and optimal implementation of both centralised and decentralised resources at the different system level through proper

energy market interaction. For example, using on-site gas-fuelled CHP systems to respond to volatile electricity market prices in a wind-rich energy system [21];

- Increase the progress of decarbonisation. With the deployment of many high efficient DGs and REs, the carbon emission has been greatly reduced compared with traditional independent energy generation fuelling on coal, petroleum and gas;

- Increase the energy system flexibility. Energy vectors could be converted to function as another energy form. For example, the heating load could be supplied by electricity using electric heating or electric HPs, which intrinsically featured with heating storage technology, it could also play a role in providing frequency response and reserve to provide electricity system balance. Or using gas-fired CHP to participate in frequency response to support local energy demand.

During the conceptualisation, formulation, implementation and evaluation of a multi-carrier energy system, problems and difficulties occur to include different energy vectors and services within a whole framework. To be more specific, there are four categories to be highlighted to typically characterise multi-carrier energy system, which are:

- The spatial perspective. This highlights how different energy vectors and services are able to be integrated at different levels. The coupling sizes or levels between multi-carrier energies may vary from building-level, for example, EH system to aggregate different types of energy generations and energy conversion components within a household, to district-level, for example, an area with crucial DG and district heating (DH) system, and finally to regions and even to countries. Geographically feasible to integrate different energy source is a very important aspect of the planning and dispatch in the multi-carrier energy system.

- The multi-service perspective. This is focusing on the provision of identifying single or multiple types of energy service or energy outputs are required in a multi-carrier energy system. It is a bottom to top scheme to find the type of service first, then up to the transportation section and thereafter up to the energy production from multiple energy carriers. The optimal interaction of different energy vectors is relevant to the multi-services required at the demand side.

- The multi-fuel perspective. This shows how different types of energy fuels, from traditional electricity and natural gas to RE such as solar energy, wind power and biomass to support for both electricity and heating/cooling load. It also represents how these fuels to be aggregated for multiple purposes in terms of economic and environmental optimisation to be in multi-service in the multi-carrier energy system.

- The network perspective. In an multi-carrier energy system, there are different energy network such as electricity network, natural gas network, DH and cooling network and so on. These networks are playing crucial roles in multi-carrier energy system in terms of facilitating the deployment of energy conversion technologies and their interdependence to reach optimal purpose.

The general categories above for multi-carrier energy system is not a conventional one perspective with a single purpose. They schematise overall features of a multi-carrier energy system. To facilitate the development of multi-carrier energy system, some categories may have significant overlapping among the different categories, which also further demonstrate the complexity of the whole system. The following content will introduce each perspective of the multi-carrier energy system in details.

2.1.1. The Spatial Perspective

From a spatial/geographical aspect, the idea of a multi-carrier energy system could be evaluated at different levels, which is able to range from individual buildings to regions or countries levels. The schematic illustration of the spatial perspective is shown in Figure 2-1.

In Figure 2-1, multiple energy vectors and services could be interacted within buildings, districts, regions and countries. For example, at small-scale individual dwellings level, the energy input would be electricity and natural gas as fuels for different power equipment such as CHP, HP, boilers, chillers and heating storage to produce electricity, heating and cooling for the use of individual demand. The operations of this equipment are coordinated optimally with different purposes such as maximising bill savings or minimising environmental impact. At district levels, the different area could also interact with each other through different energy vectors and DGs and a district heating system. Nearby districts could also participate in the integration of different energy system as a next step to scale up the concept of the multi-carrier energy system to city and region level. In order to realise the aggregation and optimisation of a district energy system, the delivery of the transport service is required.

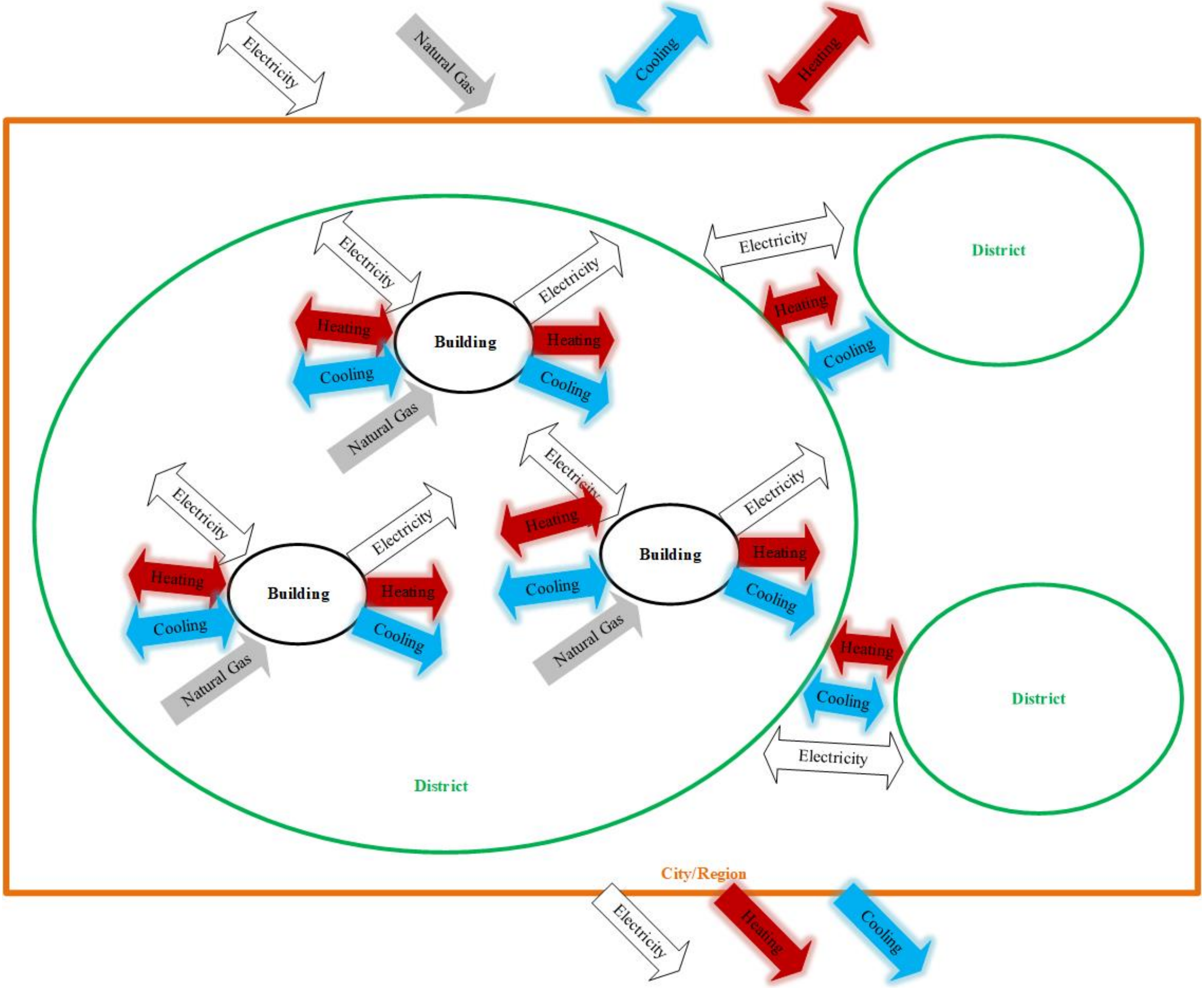

Figure 2-1. Spatial Perspective Schematic of the Multi-Carrier Energy System [21]

However, no matter what level of the multi-carrier energy system is, the key point is to model the system with a detailed illustration of the complexity and the systematic analysis to achieve a specific purpose. In particular, consideration is required to take spatial/geographical perspective into account such as the different practical network constraints.

Many research has been studied multi-carrier energy system at various spatial levels. For example, the smallest scale of the multi-carrier energy system is a building-level, which is also represented by an energy hub system [22, 23]. EH model approach is proposed to have energy production, conversion, storage and consumption of various energy carrier to take place. This small scale concept is a very promising option for the management of the multi-carrier energy system [24].

By scaling up the level from separated households to the next geographical stage, many studies have been proposed to describe the coupling of different energy supplies and demands at the district level or city level. Due to the availability and high density of different energy loads in urban areas, the multi-carrier energy applications are particularly developing and have penetrated in different district-level and city-level. Individual energy infrastructures like electricity network and natural gas network which were solely operating have coupled with each other owing to the main drivers of cost-effectiveness and environmentally friendly. Particularly with the technology development and increasing implementation of CHP, many pioneering works have been carried out to assess the options of interacting electricity network with heating supply.

Early research on multi-carrier energy system at district-city level studied competition and synergy between energy technologies in municipal energy systems [25]. It proposed a dynamic energy optimisation model named DEECO as a tool to analyse competition and synergy of different energy and renewable technologies. The proposed model is proven to provide a flexible instrument to support investment decisions when building or restricting municipal energy system. In a similar outlook, an optimisation based design of a district energy system is introduced in [26]. It built an eco-town system that allows carbon emission reduction for energy service of at least 20% at no extra-costs compared to business-as-usual using grid and boiler. Mixed integer linear programming (MILP) is the optimisation solver used to design and optimise the district-level multi-carrier energy system.

While previous literature is focusing on the optimisation of multi-carrier energy system in the district/city area, other research has paid their attention to the operations and control strategies of the system. The work in [27] has conducted an analysis of the energy and economy of a district heating system. An optimisation model was developed to obtain optimal flow and supply temperature and make operating strategies accordingly. Using small pipes in the DH system resulted in a most energy-efficient and cost-effective design. By adding RE in the multi-carrier energy system, research in [28] built an urban energy system. A three layers of the electric grid, cooling network and heat network schematic is proposed to enable spatial energy demand, supply and energy flow. Surplus electricity is converted to thermal energy and using urban PV and wind power to increase renewable fraction.

By scaling up the spatial level from district/city level to region level, there are also some studies on multi-carrier energy system. However, with the scale becoming large, the complexity of the system makes it difficult to propose a comprehensive as well as careful solution for such a large system. Research in [29] managed to solve it by developing a bottom-up linear programming model to support planning policies for promoting the implementation of REs. The modelling framework is enhanced in order to adapt to the model to the characteristics and requirements of the region under investigation. By following the environmental and economic signal, a set of feasible generation settlements are provided in this work.

To summarise, different planning, operation and control strategies were proposed according to the different spatial/geographical levels of the multi-carrier energy system. Specific consideration in terms of the feasibility of different energy resources, centralised/ decentralised energy generation and energy technologies should be carefully taken into account in the presence of spatial constraints.

2.1.2. The Multi-Service Perspective

Different energy services could be interacted with each other to provide multiple services in a multi-carrier energy system, this includes electricity, heating, cooling and energy transportation. They are generally called the outputs of the multi-carrier energy system. The schematic illustration of the multi-service perspective is shown in Figure 2-2.

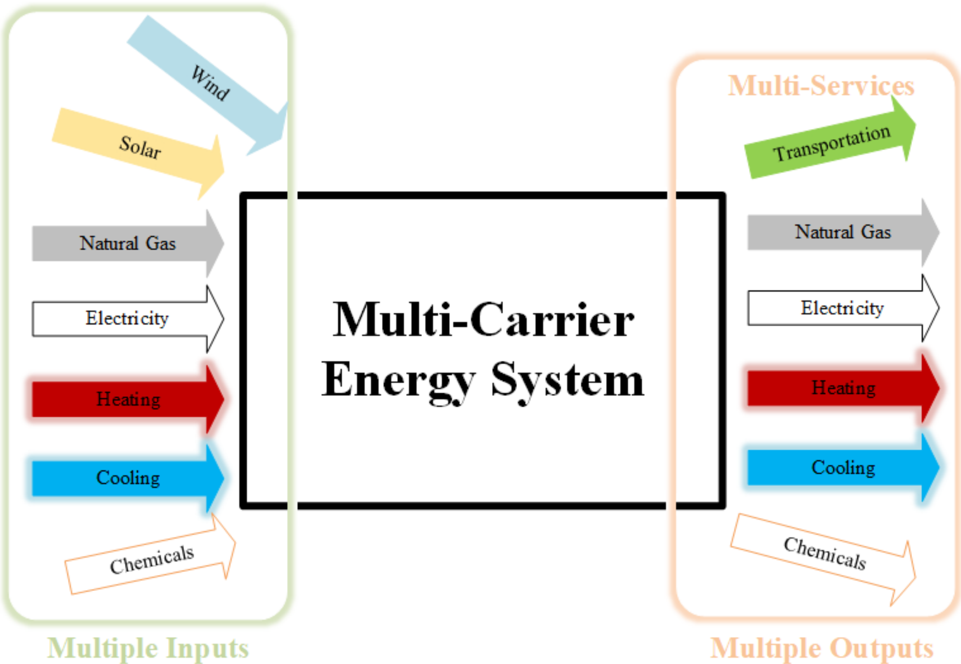

Figure 2-2. Multi-Service Perspective Schematic of the Multi-Carrier Energy System

Figure 2-2 illustrates the multiple energy services that are available in a multi-carrier energy system. The services could be regarded as the outputs. The services provided by the production of the system give opportunity and possibility to improve the system performance and drive to techno-economic and environmental benefits. A typical example would be the deployment of CHP would absorb by-product wasted heat during the electricity production and reuse it to supply local water/space heating. A combined cooling, heat and power (CCHP) system would furtherly recover wasted heat to support either heating or cooling demand.

This process of combined production of multi-energy vectors such as electricity, heating and cooling from a single type of energy source as also known as the multi-generation or polygeneration [30]. CHP and its extension of CCHP are two typical types of multi-generation techniques. Multi-generation has great potential to benefit the system in terms of economic, carbon emission and energy compared with traditional energy generations.

The further application of different multi-generation including hydrogen, chemicals, and waters and so on and how it is integrated into a multi-carrier energy system is comprehensively studied in the work [31]. It also presents how to improve the characteristics of local energy production, integrate the concepts of distributed energy resource (DER) and combine different energy vectors into the distributed multi-generation framework, and review on the various approaches to energy planning that are currently available. Another similar literature gives an overview of the multi-generation and efficient use of natural resources. It discussed the concepts of energy integration with various examples of multi-generation systems, showing that with the implementation of multi-generation, the efficiency of natural resources is significantly increased [32]. Further detailed operations and configurations of the multi-generation systems for an agro-food industry are proposed in [33], conceived for a dairy industry which requires old, heat power and water. Different configurations are discussed depending on the required demands, thermal desalination or reverse osmosis. In [34], the different environment of seawater desalination of the optimal design of a CHP system is proposed. By building an analytical model and examining the required data, an objective function is defined considering the physical constraints and cost balance. This proposed model is proven to be flexible and suitable for comparative applications in all Mediterranean countries. Another interesting work managed to integrate a biogas generation system, a fuel cell system and a green house in the bioethanol plant to form a multi-generation system. Meanwhile, the possibilities of heat energy integration to find the best utilisation of energy flow generated or consumed has been investigated in order to further reduce the consumption of external energy sources [35]. The development and assessment of an integrated biomass-based multi-generation energy system are investigated in [36]. It proposed a novel six outputs in the multi-carrier energy system and carried out a comprehensive assessment of energy, exergy and environmental impact of the proposed system. Results showed that the proposed multi-carrier energy system could reduce carbon emission by 2500 tonnes/MWh compared to traditional power generations with increased efficiency of 14%.

The above literature has focused on the performance of multi-generation with multi-services in different locations and environments and is proven to be superior to conventional means of power generation. Another aspect of multi-service of a multi-carrier energy system is the effort on the decarbonisation of the transportation process of the system. Transport is a crucial part of the multi-carrier energy system context. For different types of energy vectors, there are various kinds of characteristics of transportability. Some energy may share similar characteristics of transportability but different storabilities like electricity and hydrogen. In [37], the synergies and interactions between electricity and hydrogen with their respective application to transport are introduced. A further interdependence between electricity and hydrogen in a multi-carrier energy system is highlighted.

2.1.3. The Multi-Fuel Perspective

In the multi-fuel aspect of multi-carrier energy system context, a bunch of energies play a key role as the inputs to the system. The inputs (fuels) and the outputs (services) are two ways of a multi-carrier energy system to interact with external networks. Figure 2-3 illustrates the multi-fuel as input to the system.

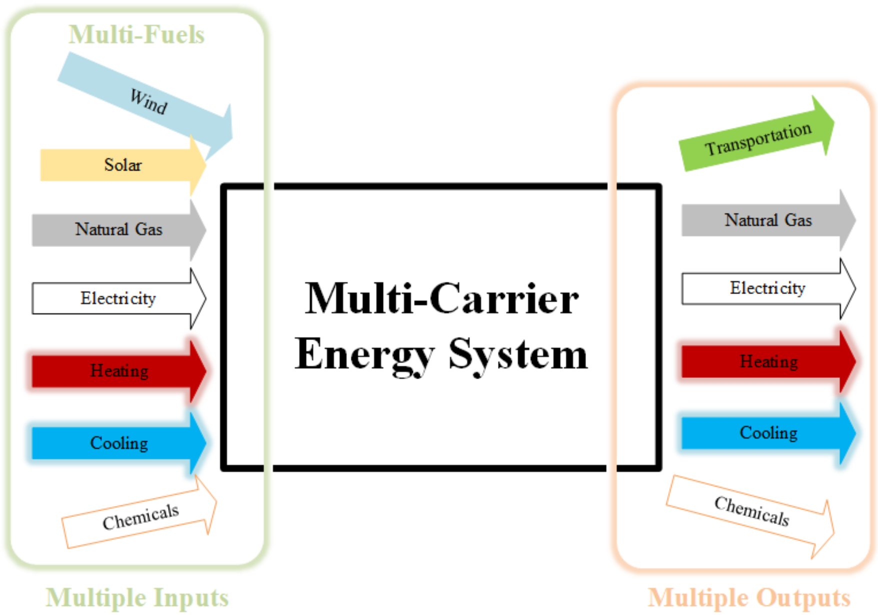

Figure 2-3. Multi-fuel Perspective Schematic of the Multi-Carrier Energy System

There are traditional energy fuels like electricity, natural gas and oil in the multi-carrier energy system. With the penetration of REs, new energy fuels could also participate in the system.

Heating, cooling or even waste exhaust are allowed to enter this system under certain circumstances. Multi-fuel is particularly momentous to analyse the system as they represent the initial interaction with the external energies and networks.

One of the interest from the multi-fuel perspective is its ability to optimally deal with waste in a system context, which is well discussed in the work [38]. This research optimises the use of waste in the future energy system including both heat and electricity market by modelling innovative waste-to-energy production plants to enable more efficient and flexible use of waste. It gives the reader a clear analysis including economical operation and investment optimisation for both electricity and heat network. There is also some literature to study energies like biomass and other less mainstream energy. The work in [39] presented a MILP modelling approach for basic components in a biomass supply chain including supply, processing, storage and demand of different types of biomass. It focused on the representation of the relationship between moisture and energy content in a discretised framework.

In recent years, with growing attention to conventional fossil fuel based multi-carrier energy system, CHP technology implementation on the system have been studied. Research on the performance analysis of CHP in terms of economic, technical, environmental is conducted. Another interesting topic would be the RE-based multi-carrier energy system. Comparisons between conventional fossil fuel CHP and renewable are made in various aspect. Arguments on whether DE will be still playing a significant role in the future development of an multi-carrier energy system, especially facing the technological shift toward large-scale HPs power by renewable electricity continues. The technology shift trend brings questions and difficulties like the coexistence or the overlapping of different types of energy vectors and technologies such as traditional DER and new REs. In [40], the authors proposed a new systematic procedure to select and size a multi-generation plant from natural gas and REs. By following a multi-criteria of energy savings, greenhouse gas emission reduction and economic feasibility, different types of energy are selected to supply the system. A similar study in [41] investigates the cooperation between a hybrid PV-CCHP and a battery storage system. This hybrid system could be coupled to an absorption chiller to use waste heat. It proposed two novel models named PV-trigeneration Optimisation Model and Canadian Hybrid Residential End-Use Energy and Emission Model to formulate the system. Results show that the hybrid system is more effective at emission reduction compared with centralised power plants with household heating technology.

Another aspect in the multi-fuels is the balancing between supply and demand within the system. Contingencies and measures will be taken place to deal with the imbalance between supply and demand, for example, CHP could recycle wasted heat to compensate the heating supply shortage and the surplus electricity generation could be sold back to the electricity market. To achieve this, a key factor is to greatly increase the flexibility of the system. Thought REs have an increased deployment globally, some of them such as wind and solar have the drawbacks of high geographical and temporal variability. Such drawbacks would require flexible energy rescuers to be taken into the consideration of the system planning and operation. Thus, research in [41-45] considered different flexibilities such as HP for demand side response, integrated electric vehicle charging functionality to stabilise the grid and support large-scale REs. Some are realised by transforming electricity into thermal and some by transport energy. It makes the multi-carrier energy system consistent with the utilisation of both REs and DGs.

2.1.4. The Network Perspective

The interconnections are taking place through different energy networks which carry different energy vectors such as electricity, natural gas, heating, cooling and so on. Figure 2-4 shows the interconnections through different energy network in a multi-carrier energy system.

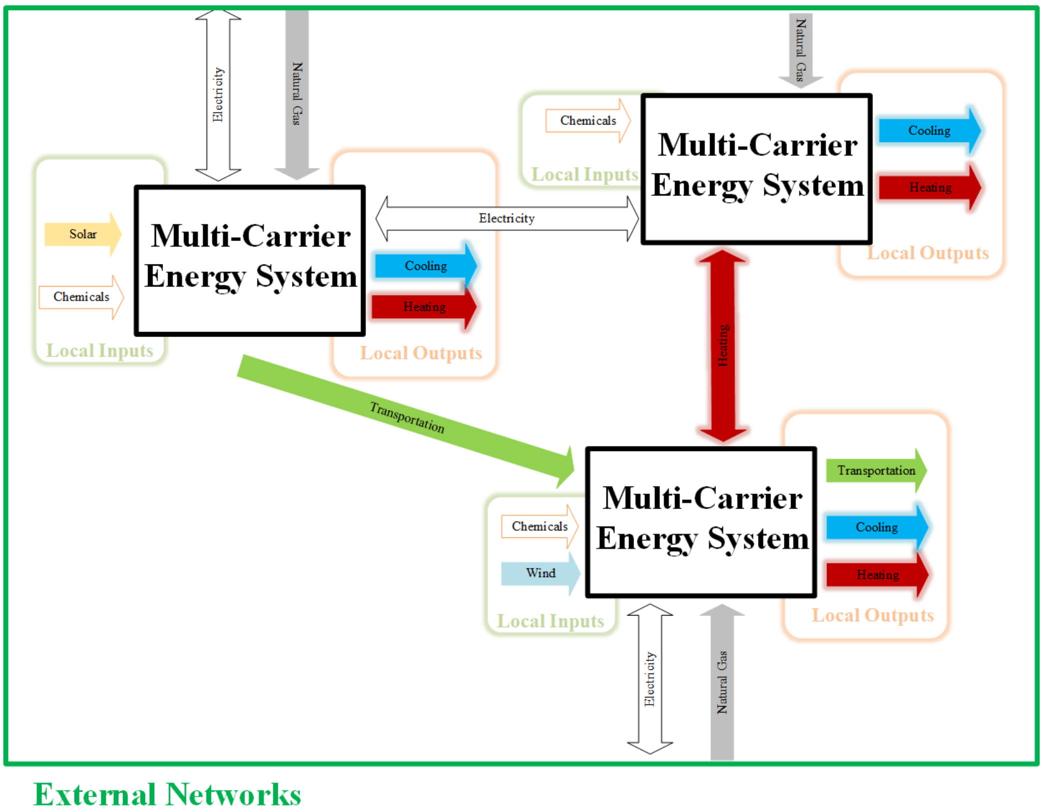

Figure 2-4. Network Perspective Schematic of the Multi-Carrier Energy System [21]

The illustrative schematic in Figure 2-4 shows the role of multi-carrier energy systems interaction among each other and the interactions with external energy networks. The local inputs are more based on the DGs and REs, while external network inputs are mainly from traditional energy vectors such as electricity and natural gas.

Many multi-carrier energy system studies in terms of network perspective are carried out. The work in [46] studies the integrated energy conversion system in certain urban areas based on geographical information and limitation. This tool designed in this research is able to study the emergence of more efficient cities that realise energy efficiency measures, integrates energy efficient conversion technologies and promotes the use of endogenous RE. A similar effort is made in [47] that proposed a systematic approach to natural gas usage for domestic heating in urban areas. The interaction between the electricity network and the natural gas network is assessed in this work. Other studies on the physical aspect of the multi-carrier energy system are conducted in [48]. A complex energy flow analysis of the integrated electrical and natural gas network is conducted in [49], using a deterministic energy flow solution by the sample generated from the Monte Carlo simulation. As sharing energy or interacting with decentralised HP units often results in relatively large heat transfer exergy losses due to the large temperature difference that is economically required from the water network, a new system is developed using refrigerants like CO_2 as a DH or cooling fluid at an intermediate temperature to alleviate this drawback. Results show that the proposed CO_2 network is favourable in terms of both exergy efficiency and cost.

The study in [50] proposes a comprehensive theoretical framework for modelling power flow of different energy network in a multi-carrier energy system based on EH concept. The coupling of different energy infrastructures such as electricity, gas and DH system is conducted. The power flow model includes conversion and transmission of an arbitrary number of energy vectors. A detailed description of a framework consists of EHs, interfaces for network participants and energy interconnectors which transmit several forms of energy is conducted in [51]. It proposes a principle scheme for multi-carrier transmission, established a set of models, evaluated the achievable performance under realistic assumptions and finally determined a suitable application range. The same research team also developed a relevant analysis framework in [52], which could be used for the planning of multi-carrier energy system including generation, transmission and the possibility of additional conversion of multi-energy carriers at different levels of energy chain and conducted a costs and risks assessment.

2.2. Planning Criterion in Multi-Carrier Energy System

2.2.1. Generalities on the Methodology

In addition to understanding different aspects of the multi-carrier energy system, to perform analysis and optimal planning and operation of the multi-carrier energy system, it is important to propose a robust assessment methodology and indicator to evaluate the performance of the system. This is according to the objectives such as from energy, technical, environmental or economic perspective.

To achieve that, it is crucial to understand the different categories of performance indicators within it. There are five basic categories in the multi-carrier energy system optimisation problem.

- The first category refers to different temporal horizons. For example, to study the system from the dynamic perspective or a static perspective, from secondly, hourly up to monthly or annually.
- The second category refers to different objectives. For example, from an economic perspective, from an environmental perspective or from an operational to investment perspective.
- The third category refers to an absolute value or relative value. While the absolute value is obtained from the results of the optimisation problem, the relative value is gained from the comparisons between the proposed methodology and a reference energy system.
- The fourth category refers to the single or multiple objectives of the problem. Some studies would focus to achieve a single target while others would try to make a trade-off between different objectives. There is also another way to achieve multiple objectives by reaching different goals at different planning/operating stage.
- The fifth category refers to a deterministic solution or probabilistic solution. The former one uses deterministic algorithm and analysis to receive a certain answer to the problem while in the latter case, the inputs/outputs of the optimisation problem are represented by probability distribution functions rather than deterministic values.

The selection of assessment criterion and approaches are based on the idea of the author would like to express and the type of different energy vectors and services within the system. For example, if an investment recovery assessment is required, the author would probably choose a long time horizon or if solar or wind technology is integrated into the system, a probabilistic approach would be more appropriate than deterministic approach as to the better prediction of wind and sun radiation. With the numbers and types of different energy indicators entering multi-carrier energy system, the choice of evaluation methodologies and performance assessment criterion is becoming more difficult.

In the recent multi-carrier energy system analysis, energy indicators are being considered more from a regulatory point of view to increase the implementation of the system, therefore it is fundamental to provide a comprehensive analysis of them. The environmental impact methodologies and the criterion to assess it are becoming critical. In the end, a techno-economic and financial assessment with the environmental impact of different energy services will be crucial and appears to be more momentous with regards to the investment budget and the increasing prices of energy, changing patterns of demand. In common practice, the merge assessment of considering both economic and environmental perspective has been widely used. The following content introduces some commonly used criterions in multi-carrier energy system planning and operations.

2.2.2. Energy Assessment Criterion

The energy efficiency characteristic of individual energy component is generally related to the input and output efficiency, for example, heat to electricity ratio (HtER) for CHP system, Coefficient of Performance (CoP) for HP. The evaluation of such an energy component could be on the different temporal horizon from minutes to up to annual resolution or lifetime to tackle financial savings compared with InC. However, such absolute efficiency to indicate energy characteristics sometimes may not be persuasive or adequate for the reader to illustrate the overall performance of the energy components in a deeper context because lacking reference case such as conventional separated means of energy systems to make a comparative demonstration.

Recent research used a comparison between the proposed multi-carrier energy system and traditional independent energy systems for demonstration. The work in [53] discusses and clarifies the definition of the European Directive for CHP. It presented a method to calculate primary energy savings and HtER and the cogenerated electricity. The extension has been made to the CCHP systems. Similar work could be found in [54] with a comprehensive evaluation of primary energy savings for energy planning and policy development. In addition, the key aspect of establishing the reference efficiencies for the conventional separate production of electrical, thermal and cooling power is addressed in detail. This aspect affects both equipment selection and potential profitability of the considered solutions under the outlook of receiving financial incentives. The same team also proposed a unified model for energy and environmental performance assessment of natural gas-fuelled multi-generation systems [55]. Another evaluation indicators for energy-chemical systems with multi-fuel and multi-service is proposed in [56]. Alternatively, a novel electricity oriented incremental indicator is carried out in [57, 58] for the planning evaluation and economic assessment of a CHP system with HPs considering the limitation of economic applications.

2.2.3. Environmental Assessment Criterion

Environmental impact is also a critical perspective to study the performance and the quality of a multi-carrier energy system. The discussion on the emission is basically comprised of two parts: one is global emissions and the other is local emissions depending on the reference of the spatial/geographical level.

The most common global environmental impact would be the carbon emission reduction to reflect the progress of decarbonisation. As CHP, DG and some REs would have a significant reduction in the carbon emission in the aggregated energy network, there are many kinds of literature studying the performance in this aspect. The work in [59] focuses on the carbon emission of the cooling process in chillers based on black-box models. There are other global environmental impacts from global warming, for example, the work in [60] studied the reduction of SO_2 and R11 of a CHP system. It claims that more attention should be paid to acid precipitation and stratospheric ozone depletion than global warming, which is three important energy-related environmental issues.

The local environmental impact from REs, DGs and other energy technologies in a multi-carrier energy system is more confined to a portion of the area. For example, the research in [61] discovers that the implementation of DG alternatives could increase local pollution in particular due to CO and NO_x and probably worsen the local air quality. Similar works in [62] discuss environmental aspects concerning the local variations due to pollutants such as sulfur oxides SO_x, particulate matter and nitrogen oxides NO_x by using a dispersion model to evaluate such effect at a local scale.

Life cycle assessment combines a set of the criterion in terms of environmental impact and ecosystems and becomes popular as indicators in the multi-carrier energy system performance. The author incorporated environmental information obtained from LCA with a MILP to optimise the synthesis of CCHP system and combined economic and environmental aspects to design a multi-criteria for the planning of CCHP systems [63, 64]. In addition, the work in [65] evaluated the possible emission reduction by means of LCA methodology to provide some guidelines regarding the environmental feasibility. In terms of regulations and policies legislated for energy technology environmental effect, an overview of existing tools and methods for environmental assessment in terms of policies from different legislations is introduced in [66].

To summarise, there are a vast number of studies to investigate the environmental impact of the multi-carrier energy system and the energy technologies within it, due to the fast-growing attention to the global warming and climate change.

2.2.4. Economic Assessment Criterion

The economic assessment would the key point in the performance analysis of any kind of energy system or energy technology. Economic indicators are regarded as one the most significant index to evaluate the multi-carrier energy system. Generally, economic assessment is comprised of two aspects: planning and operation. The planning aspect refers to the optimisation to achieve a certain goal of the system. For example, to minimise the energy cost by determining the optimal location, the capacity of different energy component to meet the demand for a certain type of single energy network or multi-energy system. The best solution and ranks for various energy alternatives at a design stage. The operation aspect refers to the operation of different energy services on the basis of the relevant energy prices. For example, to maximise the bill savings by providing optimal operational strategies for each component within the system. The nature of the economic assessment could be either based on deterministic or probabilistic. The deterministic model is based on given data and a probabilistic model is based on at least one of the variables extracted from the stochastic model or probability distribution function.

Deterministic-based economic model assessment is a very common planning multi-carrier energy system. In the book [67], the planning and evaluation of DGs are explored. Detailed preparation and analysis of DGs for different customer types such as residential, commercial and industrial are demonstrated as well as electric utility applications. Comparisons are made between DGs and traditional centralised power plants in terms of planning cost and reliability evaluation.

The purpose of the optimal operation is more focusing on the revenue cost and profit within a planned horizon. The time scale considered in the study is normally associated to the energy load. High time resolution such as every minute operation management could usually be applied in some electricity balancing market. The hourly analysis is related to the real-time changing price of the energy vector. Long-term analysis on monthly basis or annual basis are probably in need to capture seasonal effect or to estimate the capital recovery horizon. The emerging studies on the probabilistic or stochastic economic-indicated model assessment have drawn the attention. The use of the probabilistic model is mainly due to the increasing degrees of uncertainty that is introduced into the multi-carrier energy system. A probabilistic model is also commonly used in some renewable technologies such as wind power and PV to accommodate the uncertainty [68-73]. Some interesting literature has converted the environmental impact into the environmental cost to quantify the effect in an economic manner. For example, an environomic approach for the modelling and optimisation of a DH network based on centralised and decentralised HP, CHP and gas furnace with the methodology and application is proposed in [74, 75]. The importance of this work is to design a general model including environmental, thermodynamic and economic characteristics.

2.3. What is Combined Heat and Power

2.3.1. Definition of CHP

Combined Heat and Power is also referred to as cogeneration or total energy. It is a unique process to produce electricity and recycle by-product exhaust into usable heat at the same time. An extension from CHP to generate cooling by using an absorption chiller unit is called Combined Cooling, Heat and Power or trigeneration.

Generally, the heat in the engine is used to do mechanical work and once the work is done, the remaining heat in the engine will be dissipated into the air. However, CHP is able to capture this wasted heat from the electricity generation process and reuses it for other heating purposes. Thus there are three basic stages during the operation in a CHP in sequence:

- Electricity Generation
- Heat Recovery

- Heat Reuse

CHP is preferable for a site with both large and continuous electricity and heating demand. The energy conversion from electricity into heating has a number of advantages such as providing alternatives for heat demand and relieve the pressure of peak time heat load. Therefore, in some cases, using this simultaneous electricity and heat generation technology could turn a marginal CHP case into a viable option.

CHP is also a flexible energy conversion technology to fit in any systems where the heating demand is required. It is particularly suitable for residential, commercial and industrial sectors. The CHP application could be therefore categorised in three according to their sizes: large-scale CHP, small-scale CHP and micro-CHP. The large-scale CHP system is often referred to as the customised CHP system for large industrial sectors. The small-scale CHP system is generally used for some small-sized industrial applications or for commercial sectors such as supermarket and hospitals. Micro-CHP is more implemented for domestic or small commercial purposes.

CHP systems could also be categorised into packaged CHP system and custom-built CHP system according to their operation purposed. In general, packaged CHP are employed for small-scale application as they are designed and manufactured in a modular fashion in large numbers. Packaged CHP system usually has a small electrical output less than 1MWe. It is widely spread in the small commercial and residential sectors such as hotels, leisure centres, hospitals, gyms and small community heating schemes. Custom-built CHP system is configured and designed in a less common manner for specific applications. This kind of CHP system is generally used in industrial sectors such as chemicals, oil refining, paper and food.

Compared with traditional independent electricity and heating generation using power plant and boiler, CHP enables to make more efficient utilisation of the primary energy fuels. This indicates a high energy efficiency with less environmental impact and reduced primary energy savings. A simple illustration of energy savings of the CHP system compared with traditional separated generation is shown in Figure 2-5.

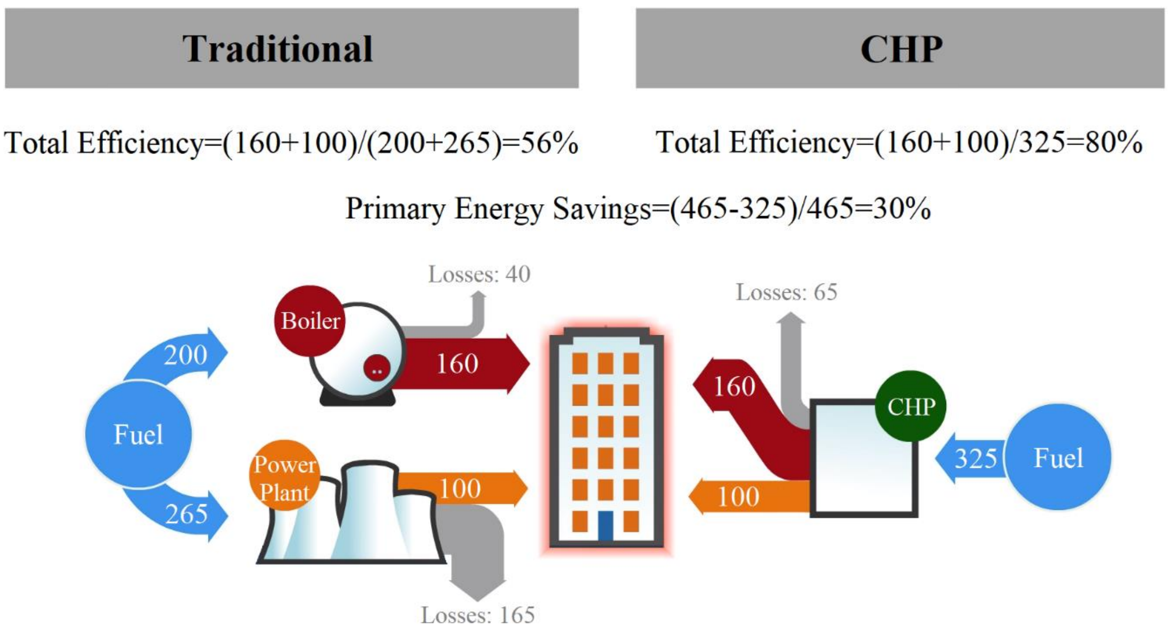

Figure 2-5. Primary Energy Usages of CHP and Conventional Generations

Figure 2-5 shows the typical fossil fuel usages of CHP and traditional electricity and heating generation through power plant and boiler separately. The efficiency of fossil fuel electricity generator and traditional boilers are 38% and 80% respectively, with an overall efficiency of only 56%, while providing the same amount of energy for heating and electricity demand, the overall efficiency of a CHP system is 80%. Thus the primary energy savings by using a CHP system rather than conventional means is about 30%.

2.3.2. Benefits, Policies of CHP in the UK

With the improvement of the technology in a CHP system, the capital cost of it has been reduced. However, CHP systems, especially the custom-built CHP system, require tremendous capital investment and resources. This high outlay is balanced by the advantages of cut energy cost, reduce carbon emission and provide a secure and reliable energy supply with improved energy efficiency.

- Lower costs. In general, a CHP system is proven to reduce total energy bills by 20-30% compared with traditional decoupled energy generation like electricity and natural gas.[76]
- A better environmental performance. This performance could be categorised into three aspects. First, as the primary energy fuel consumed by energy generated per unit is much lower than traditional means, carbon emission from the generation process is much lower. Second, high GHG emission fuels such as coal mine and oil in traditional

electricity generation could be replaced with cleaner fuel with lower carbon emission like natural gas. Third, as CHP is operating locally on site, it cut the energy transmission. Therefore, it greatly reduces the losses for large-scale electricity generation to be transmitted over a very long distance. With the increasing awareness for global warming and climate change of the public, CHP shows the commitment to reduce the energy consumption with less GHG emission and improved sustainability.

- A more reliable and secure supply. CHP could be able to generate both electricity and heating independently, it reduces the dependency of the customer on the electricity network. It could be used as a balance mechanism to the peak demand and benefit the users to sell surplus electricity back to the network. An off-grid synchronous generator based CHP system could supply the local user completely from the import from the network, it could also use as a back-up in case of any power failure. By reducing the dependency of local customers on the main network, it improves the security of the energy supply.

The government of the UK have been supporting the development of CHP in many years, many regulations and policies have been proposed to bring more benefits deployment of CHP schemes.

- The CHP Quality Assurance programme

CHP Quality Assurance programme is a government initiative providing a practical, determinate method for assessing all types and sizes of CHP schemes throughout the UK [77]. It introduced a quality index to assess the performance of the CHP schemes by measuring the overall efficiency of CHP and calculating the primary energy fuel savings compared with traditional decoupled energy generation like electricity and heating. This quality index is calculated using the following equation[77]:

$$QI = X \times \eta_{Elec} + Y \times \eta_{Heat} \qquad \text{(Eq. 2-1)}$$

Where η_{Elec} and η_{Heat} are the electricity efficiency and heat efficiency of the CHP system respectively, X and Y are the factors vary depend on the size, fuel type and technology of the CHP system. These two factors are used to ensure the CHP scheme also meet the requirement of the European CHP Directive.

The standard of a Good Quality of CHP is considered to have an electrical efficiency of over 20% with the Quality Index above 100. The CHP schemes certificated as Good Quality could be registered for many following incentive policies published by the UK government.

- The Climate Change Levy reduction or exemption

The Climate Change Levy is introduced on 1 April 2001 under the Finance Act in 2000 under parts of the UK's Climate Change Programme. It is a tax to be paid by the non-domestic user aiming to increase the energy efficiency and reduce carbon emissions. The latest rate published from 1 April 2018 is in Table 2-1.

Table 2-1. Tax Rate of Various Energy Source of Climate Change Levy[78]

Taxable Commodity	Tax Rate	Climate Change Agreements discount (%)
Electricity	0.583 p/kWh	90
Natural Gas	0.203 p/kWh	65
Liquefied Petroleum Gas	1.304 p/kg	65
Any other Taxable Commodity	1.591 p/kg	65

If the customer using a CHP system is registered as GQCHP and able to export electricity to the network, a Levy Exemption Certificate could be received to reduce or get exempted from the Climate Change Levy. If the CHP system holders could successfully register for a Climate Change Agreement published in 2014, a further discount could be applied to reduce the Climate Change Levy tax.

The Levy Exemption Certificate and Climate Change Agreement are two significant incentives of the government to support the development of high efficiency, low carbon emission technologies like CHP in the UK.

- Enhanced Capital Allowance

Another policy associated with the Good Quality CHP is called Enhanced Capital Allowance. The CHP schemes with Good Quality CHP is eligible to claim for an ECA, which offers 100% first year tax reduction. Not only CHP schemes, any energy technology that meets the requirement of the Energy Technology List [79] that is managed by the Carbon Trust on behalf of the government, are eligible to apply for Enhanced Capital Allowance. It benefits the users by improving the cash flow, relieves the economic burden for the users in the year when buy and put the equipment into operation.

- Carbon Reduction Commitment Energy Efficiency Scheme

With formerly known as Carbon Reduction Commitment, the Carbon Reduction Commitment Energy Efficiency Scheme aims to incentivise the penetration of high-efficient and low carbon emission energy technology, particularly for large energy users publicly and privately. [80]

The participants for this project is for large energy users having an annual electricity consumption of over 6000 MWh, such as universities, supermarkets, hospitals and local authorities. The participants must have a carbon allowance for their carbon emission, as well as monitor and report their energy use annually. The participants have two options of paying the annual carbon allowance: by paying in advance with lower forecast sale price or by paying after the end of the compliance year with a high compliance sale price. The Carbon Reduction Commitment Energy Efficiency Scheme prices of the last five years shown in Table 2-2.

Table 2-2. Carbon Price for the Current Phase of Carbon Reduction Commitment[81]

CRC Scheme Year	Forecast Sale Price (£/tonne)	Compliance Sale Price (£/tonne)
2014/15	15.60	16.40
2015/16	15.60	16.90
2016/17	16.10	17.20
2017/18	16.60	17.70
2018/19	17.20	18.30

- Renewable Obligations

The Renewable Obligations is also another incentive mechanism for large-scale renewable technologies in the UK. For the smaller scale generation is supported by the Feed-in Tariffs that will be introduced later.

The Renewable Obligations is published in 2002 aiming to place an obligation for the UK electricity suppliers to increase the penetration of renewable generations in both numbers of schemes and size of the capacity. The Renewable Obligation Certificates is issued by the Ofgem on behalf of the government to the network operators for the accredited renewable generations. Renewable Obligation Certificates are tradable and playing an important role in demonstrating the suppliers to meet their obligations. Renewable-fuelled CHP schemes are eligible for Renewable Obligation Certificates. The Renewable Obligation Certificates bandings of different fuel type of CHP is shown in Table 2-3.

Table 2-3. Renewable Obligation Certificates Bandings of CHP Schemes[82]

CHP Fuel Type	Power only (ROCs/MWhe)	CHP (ROCs/MWhe)
Dedicated Biomass	1.5	2.0
Dedicated Energy Crops	2.0	2.0
Co-Firing of Biomass	0.5	1.0
Co-Firing of Energy Crops	1.0	1.5
Waste-to-Energy (Biomass Proportion)	1.0	1.0

- Feed-in tariffs

Feed-in tariffs, published on 1 April 2010, and is introduced for the small scale energy user to incentivise the development of renewable and low-carbon emission generation technologies. The participants in this scheme with licensed electricity generation are able to make payments from the electricity generation and export from eligible installations.[83]

The Feed-in tariffs scheme is open to any users who have installed renewable technologies of solar PV, wind power, hydro and anaerobic digestion with a capacity up to 5 MW and CHP up to 2 kW. Participants will receive their Feed-in tariffs payment quarterly from the renewable electricity have been generated as well as exported to the network, based on the meter reading submitted to the energy supplier called Feed-in tariffs licensee. The latest CHP generation tariff is 14.52 p/kWh with an export tariff of 5.24 p/kWh.

- Renewable Heat Incentive

Renewable Heat Incentive, especially for the non-domestic sector is claimable for the business, public sector and non-profit organisations to meet the cost of installing renewable heat technologies [84].

The latest regulation for non-domestic Renewable Heat Incentive came into effect on 22 May 2018, the participants of non-domestic Renewable Heat Incentive will be paid for up to 20 years as long as the renewable technology meets the requirement. The payment is based on the actual heat output of the installation. According to the latest tariff rate of CHP system, it is 4.42 p/kWh eligible for all capacities.

- EU Emission Trading System

The EU Emission Trading System is a policy across Europe to corporate between countries aiming to combat climate change and reduce GHG emission in a cost-effective manner. This system covers and focuses on the carbon emission, nitrous emission and perfluorocarbons to be measured, reported and verified.

In the outlook of the development of CHP, as EU Emission Trading System is now it the third phase, policies have been published that the originations registered with Good Quality CHP are granted for a greater carbon allowance. This is based on the fact that CHP schemes emit more locally compared with other traditional generation which helped saving carbon emission on a global level.

2.3.3. CHP Operating Principle

As discussed in Chapter 2.3.1., the basic elements in a CHP system are the prime mover which provide the mechanical power to drive the system, the electrical generator which produces electricity and the heat recovery equipment to capture wasted exhaust to provide heat. The following content will describe each of the basic elements in a CHP system.

The core energy component of a CHP system would be the heat engine called as the prime mover. This is the part where a CHP system could generate the mechanical power to drive the electrical generator and produce heat at the same time. The prime mover is generally an internal combustion engine, a gas turbine or a steam turbine.

1) The Prime Mover

The basic types of CHP prime mover are shown in Table 2-4.

Table 2-4. Five Principal Types of CHP Prime Mover

Type of Prime Mover	Type of CHPs
Internal combustion engines	Packaged CHP
Steam turbines	Custom CHP
Gas turbines	Custom CHP
Combined cycle gas turbines	Custom CHP
New and emerging technologies	Packaged CHP or custom CHP

- **Internal Combustion Engines**

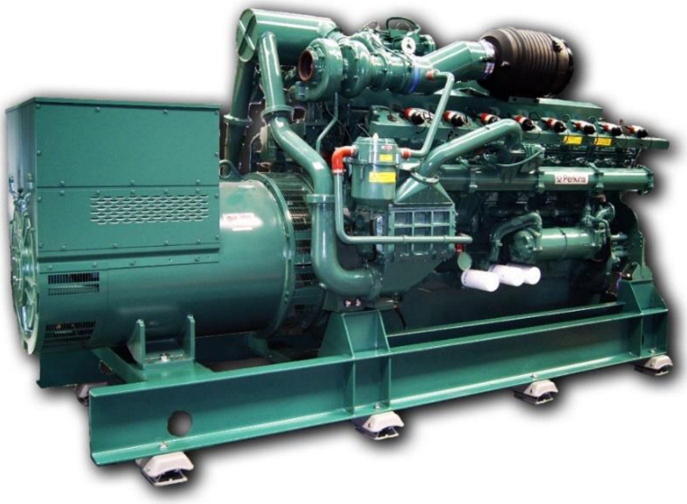

Figure 2-6. An Internal Combustion Engine CHP from E.Van Wingen [85]

Figure 2-6 shows a CHP product using an internal combustion engine as the prime mover. In the internal combustion engines, natural gas or compression-ignition diesel is burned and the thermal power is converted into mechanical power. The electricity efficiency transmitted from the internal combustion engine to the electrical generator is typically from 25% to 40%. With the bigger size of the CHP system comes with higher electricity efficiency of it. The by-product high-temperature exhaust is usually captured to provide heating water service. This heat to electricity ratio is around 1 to 2. This ratio will decrease with the capacity of the CHP.

Internal combustion engine based CHP system has a typical electricity capacity ranging from 5.5kWe up to 5MWe. Thus it is suitable for the packaged CHP system in residential and small commercial sectors providing adequate hot water services like university and accommodations, hospitals, hotels and leisure centres.

- **Steam Turbines**

Figure 2-7. Interior View of Steam Turbine Blades of a CHP System [86]

The interior view of the steam turbine blades could be observed in Figure 2-9. A steam turbine CHP system uses the high-pressure steam to provide power and driver with the turbine. Condensed steam in the turbine provides the maximum electricity efficiency and a part of the high-temperature steam is pumped back to the boiler to provide hot water.

The overall efficiency of the steam turbine based CHP system is from 77% to 83% with electricity efficiency ranges from 11% to 20%. The steam cannot be burned directly and could be used to provide a huge amount of heating in steam turbine CHP. Therefore it is used for large scale custom-built CHP system with high heat requirement.

- **Gas Turbines**

Figure 2-8. A Gas turbine CHP System from Solar Turbines [87]

Figure 2-8 shows the gas turbine CHP installation in a university. Gas turbine uses the stream of burning natural gas to provide the mechanical power passed to the electricity generator. And the high-temperature exhaust from the burning gas is captured and reused for heating purposes.

The size of a gas turbine powered CHP system is generally larger than 1MWe, suitable for large scale custom built system. The electricity efficiency of gas turbine CHP system ranges from 25% up to 36% with the increase of the CHP size from 1MWe up to 100 MWe.

- **Combined Cycle Gas Turbines (CCGT)**

CCGT-based CHP is a combined technology of both steam turbine and gas turbine system, shown in Figure 2-11.

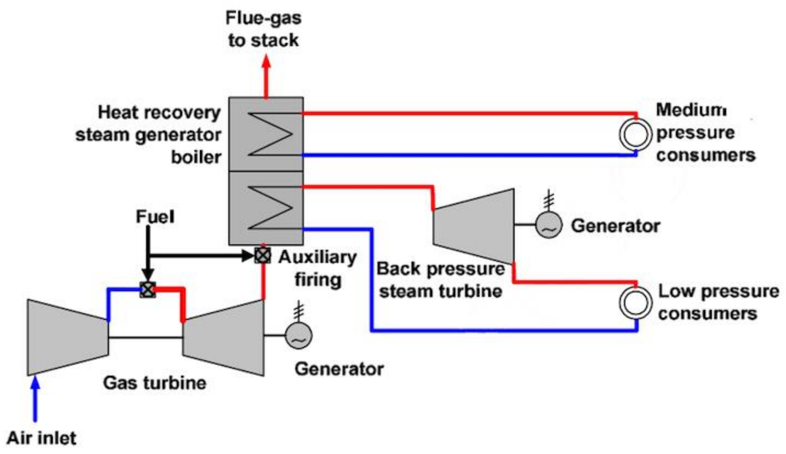

Figure 2-9. Schematic of a CCGT CHP System [88]

The electricity is generated by the motive power passed by the steam turbine and the heating is recovered from the high-temperature exhausts from the gas turbine. Such a combination provides a very high electricity efficiency compared with the prior mentioned technologies of 55%. Thus CCGT-based CHP is favourable for large-scale high electricity demand sectors. There is also an additional heat recovery system in the steam generator preventing heat loss. All CCGT-CHP system is customised for specific purposes.

- **New and Emerging Technologies**

There have been new established types of CHP system into the UK market in recent years. The most popular types would be the Stirling engine CHP [89] with relatively low electricity efficiency of 6-8% for the micro-CHP system, fuel cell CHP [90] system using electrochemically oxidising fuel and Organic Rankine Cycle CHP [91] system using a different type of working fluid.

2) The Fuel Selection

The selection of fuel for a CHP system is depending on the engine type, fuel availability, supply flexibility, storage and use. Some CHP systems could adapt to more than one fuel, which provides alternative and flexibility of supply. It also improves the security of the supply. In practice, the fuel choice is normally limited due to the environmental emission requirement.

A majority of packaged CHP system uses natural gas as the first choice of fuel, though some other gases like propane, butane, liquefied petroleum gas and biogas from sewage/landfill waste are available but less common. Other fuels like coal and oil are used for a steam turbine, however, this kind of less clean fuel type would also increase the cost of meeting environmental standards. Some CHP schemes use natural gas as a back-up fuel for a steam turbine for combustion ignition or in case of fuel shortage.

To summarise, cleaner fuel like natural gas and lighter oil of good quality with a relatively high price. Fuels like coal would be less expensive to buy, but more costly to use for energy generation.

3) The Electricity Generator

The electricity generator converts the motive power from the prime mover into electric power. There are generally two types of generator: synchronous generator and asynchronous generator. The synchronous generator is also known as a self-controlled generator, it could work solely on the grid in island mode. This independency makes it more suitable as a back-up electricity generation plan in case of any network failure. The asynchronous generator is also known as a grid-controlled generator. It requires interaction with the grid and will also get shut down in event of grid power fails. Therefore it is not favourable as a back-up option for system failure.

In terms of the capital cost of these two types of generators, for small size generator below 100 kWe, synchronous generator is much more expensive than asynchronous generator due to the installation of an additional generation control system. Thus, the asynchronous generator is more commonly seen in a CHP system unless the back-up strategy is needed. For generator size above 100 kWe, the capital difference between two generator types is small so the synchronous generator is more employed in CHP schemes with additional standby service.

4) The Heat Recovery System

The heat recovery system recovers the high-temperature exhaust or steam in the steam turbine and reuses it for heating demand. Different heat recovery systems are required according to the prime mover. For internal combustion engines, the heat recovery system contains a plate heat exchanger for heat capturing. For a gas turbine, a heat recovery steam generator is needed to capture exhaust. For some other cases, this heat recovery steam generator itself could burn fuels as supplementary firing. For a steam turbine CHP system, the heat is recovered directly from the high-temperature steam by reducing its high pressure.

2.4. CHP Modelling

To study the modelling of CHP interconnected within the multi-carrier energy system, the inputs, outputs, and CHP interaction with the system should be illustrated. Figure 2-10 shows a conceptual schematic diagram of a CHP installed in a community.

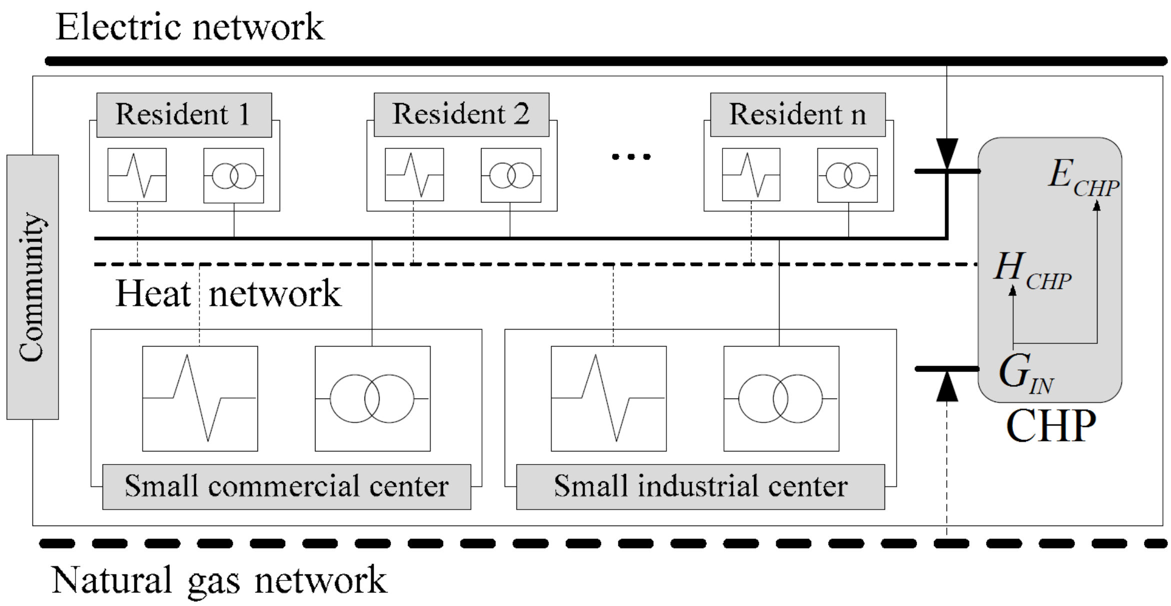

Figure 2-10. Schematic of CHP Connecting to the Multi-Carrier Energy System [92]

In Figure 2-10, the input of CHP is connected to the natural gas network while its output is connected to local electricity load and heating load. According to the technical model of the CHP system in [93, 94], there are two key parameters to describe the characteristic of CHP modelling: the overall efficiency, denoted by η_{CHP} and HtER, denoted by ζ_{CHP}. Each of them are expressed by the following equations:

$$\eta_{CHP} = \frac{P_{OUT}}{P_{IN}} \tag{Eq. 2-2}$$

Where P_{IN} is the power input, for gas fuelled CHP system, it is the input power of burning gas. P_{OUT} is the sum of electricity output P_E and heat output P_H:

$$P_{OUT} = P_E + P_H \tag{Eq. 2-3}$$

$$\zeta_{CHP} = \frac{P_H}{P_E} \tag{Eq. 2-4}$$

By substituting Equation 2-2 and 2-3 into 2-4, electricity output P_E and heat output P_H could be expressed by η_{CHP}, ζ_{CHP} and P_{IN}, respectively:

$$P_E = \frac{\eta_{CHP} \times \zeta_{CHP}}{1 + \zeta_{CHP}} P_{IN} \quad \text{(Eq. 2-5)}$$

$$P_H = \frac{\eta_{CHP}}{1 + \zeta_{CHP}} P_{IN} \quad \text{(Eq. 2-6)}$$

- Overall Efficiency

According to the study in [95], the overall efficiency η_{CHP} could be modelled depending on the level of loading, which is shown in Figure 2-11.

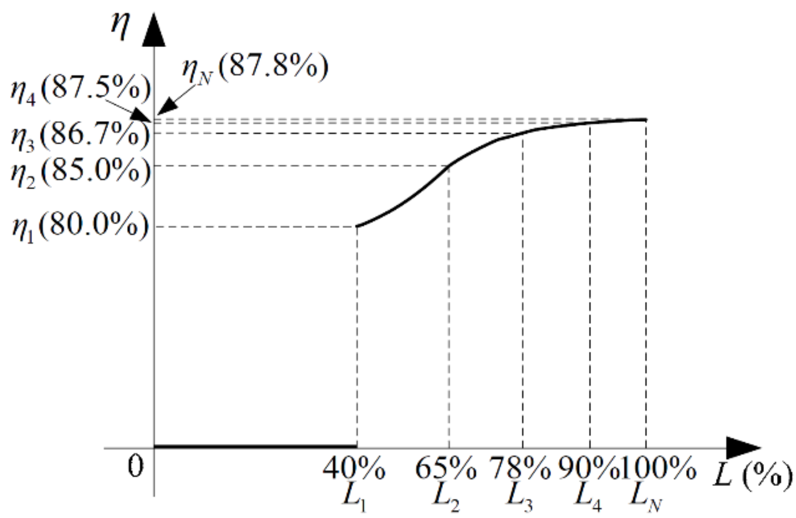

Figure 2-11. η_{CHP}-Load Level Curve [95]

This η_{CHP} and loading level curve could be modelled as a series of discrete functions of the loading level L by the following:

$$\eta_{CHP} \begin{cases} f_1(L) = 0 & 0 \leq L < L_1 \\ f_2(L) & L_1 \leq L < L_2 \\ f_3(L) & L_2 \leq L < L_3 \\ f_4(L) & L_3 \leq L < L_4 \\ f_5(L) & L_4 \leq L < L_N \end{cases} \quad \text{(Eq. 2-7)}$$

Different expression of overall efficiency is required according to a different level of load.

- HtER ζ_{CHP}

An HtER against load level diagram is shown in Figure 2-12.

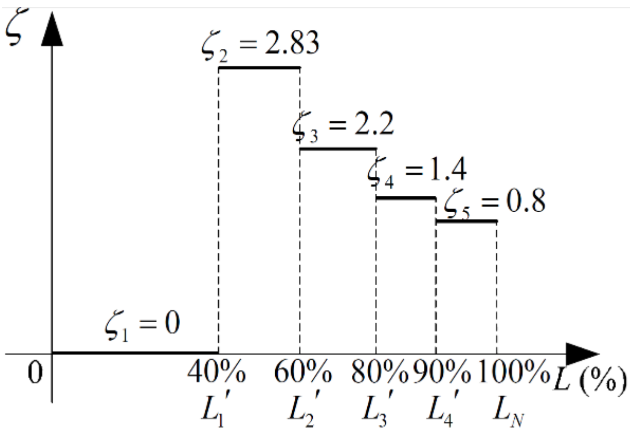

Figure 2-12. ζ_{CHP}-Load Level Curve.[95]

According to this figure, HtER could be expressed with a load level as:

$$\zeta_{CHP}\begin{cases} 0 & 0 \le L < L_1' \\ 2.83 & L_1' \le L < L_2' \\ 2.2 & L_2' \le L < L_3' \\ 1.4 & L_3' \le L < L_4' \\ 0.8 & L_4' \le L < L_N' \end{cases} \tag{Eq. 2-8}$$

Equation 2-2 to 2-8 form the static modelling of CHP system which will be applied in the following chapters for CHP planning and operation studies.

2.5. CHP Planning and Operation

This chapter will introduce CHP planning and operation in three aspects: objectives, CHP models, networks.

2.5.1. Objectives

- **Energy Reduction**

The energy assessment is one of the most commonly used objectives in the optimal CHP planning and operation. It is the most intuitionistic way to describe the primary energy to be saved by the CHP system. A vast number of studies analysed the CHP implementation from this point of view.

For example, the work in [96] uses a defined term named Fuel Energy Saving Ratio to assess the performance of various energy component in a multi-carrier energy system in many practical cases. This term FESR is defined as the primary energy saving which a CHP system could provide compared with traditional means of energy generation. In [97], a series of policies and particularly the cost-internalising actions are being empowered and as a reference in order to favour improvements in conversion efficiencies and promote low environmental impact technologies. It also discusses the expected impact of different evaluation criteria of CHP for its promotion. In [98], comparisons are made between traditional independent energy generations and CHP system to assess their primary energy savings, energy efficiency and carbon emission. An interesting review in [99] summarises the most commonly used efficiencies and other indicators of the performance of CHP. The emphasis is put on those indicators that are used in the legislation of many countries. It also discusses the state quo for the development of CHP in various countries. The work in [100] proposes equations of energetic efficiency of this the CHP system that relate the primary energy rate and comparative primary energy saving to energy parameters of designed systems. Results show that a large potential for energy saving is realised by designed CHP system. A similar type of indicator assessing CHP performance is presented, named quality index, which is carried out in [101]. It is used to assess fuel savings and CO_2 emissions for a CHP system. The work in [102] evaluates energy utilisation of a CCHP system, showing a result of conditional energy savings but not intrinsic is applied and CCHP system with larger electric power having a higher energy saving potential.

- **GHG/Carbon Reduction**

As one of the advantages of the CHP system, carbon reduction is also another popular goal to be achieved in the study of CHP optimisation.

The work in [103] discusses the environmental impact of CHP and DGs. It presented local and global emission impact models to evaluate the upper and lower boundary value of the environmental pressure from pollutants to be emitted compared with reference energy technologies. The attribution of global environmental impact refers to the GHGs for global warming such as CO_2, R11 for ozone consumption or SO_2 for acidification. The attribution of local environmental impact refers to local pollutant emission such as CO, NO_x and so on. A general idea of how CHP and CCHP make a contribution to climate change control is presented in [104]. Results show a range from 10% to 50% of carbon emission savings could be obtained using the proposed energy technologies with an optimal solution corresponding to the use of non-fossil fuel. A more complex and detailed report in two parts [105, 106] have a full assessment of GHG emission of CHP in terms of models, indicators, analysis techniques and application cases. It proposed a CHP CO_2 emission reduction and CCHP CO_2 emission reduction as indicators to quantify their environmental impact. There are also some cases studying both global and local environmental effects at the same time like [107], showing that small CHP DH system could produce critical aspects of emission both globally and locally and a pollutant concentration analysis is useful to evaluate such effects.

- **Costs savings**

Literature of CHP planning and operation consider a various type of cost savings, including fuel cost, InC, operation and maintenance cost. The economic benefit from a CHP system is one of the main drivers to the operators.

The work in [108] considers various types of cost in planning CHPs including InC, fuel cost and maintenance cost as an objective to be minimised. It proposes a stochastic programming model to determine the size and location of the components within a CHP system, auxiliary boilers and heat-storage tanks. This model is formatted in a two-stage strategy and solved using MILP. It is applied to a large residential complex as a case study and proven to be effective. In [109], a CHP plant with a DH system is optimally planning to minimise the energy cost with a linear programming model tested on a real case. Different scenarios are included to exploit energy during both summer and winter with increased heat demand. Similar work is done in [110] to provide integrated management of CCHP with DH networks. It developed a dynamic simulation of heat distribution network with a CHP system to obtain optimised management to provide economic competitiveness and energy savings. The proposed method is used in a CHP-based DH project in Italy and proven to be effective. A MILP model for the optimal design of the energy component in a hospital complex is proposed in [111]. According to the electricity and heating load, an optimal energy-management is derived from the operation of CHP, HP and DH to achieve significant economic energy and environmental benefits. Operational strategy and marginal cost in simple CCHP system are carried out to cut economic pressure compared with traditional generations [112]. In the work [113], a spark-spread ratio is introduced to describe the relationship between the electricity market price and the variable cost of electricity production based on such price. Using this indicator to assess a hybrid CHP-HP system in terms of energetic and economic benefits. In [114], a risk analysis is conducted for the optimal operation of CHP within an open electricity market. As the possibility of changing the InC, the price of district heating, natural gas and electricity are all based on distribution profile, thus the input data is uncertain and the stochastic model is required. The authors in [115, 116] manage to design a planning strategy of CHP system under uncertainties. The first part uses a multiple time frame approach and Monte Carlo simulation to represent price related random variables for the short-term and mid-term time frame. And the second part presents a decision theory-based assessment for long-term planning. Small scale CHP planning is discussed in [117] in order to minimise the expected annual cost of the system. A generic deterministic linear programming model is developed for residential demand. Similar work for the smart grid is done in [118]. A combined environmental and economic dispatch is aiming to be achieved using a distributed model predictive control. Results show a 40% reduction of the generation cost compared with traditional means of generation. The work in [119] discusses the optimal management of the EH system with CHP. It is conducted through a financial valuation of each unit of the EH and CHP considering the volatile market prices.

- **Multi-objectives/Trade-Off Objectives**

Some other literature attempt to pursue and make a trade-off between objectives mentioned previously.

Interesting work in [120] uses multi-objectives to tackle different stages of planning. In the bus location selection stage, it proposes a loss sensitivity index (LSI) obtain optimal locations for DERs. In the size selection stage, it achieves the goal by minimising the power loss in the electricity network. For the thermal and electric part of DER, it uses the economic emission load dispatch which contains NO_x emission cost and fuel cost as objective to optimise the problem. The proposed multi-stage method is done with a particle swarm optimisation method compared with differential evolution. A CHP based EH system is analysed in [121]. The authors manage to find a robust optimisation approach for the EH system of minimising a cost function including energy cost, emission cost and operation and maintenance cost. Another MILP based optimisation model to design and operate the CHP distribution generation system in an urban area is introduced in [122]. It focuses on the CHP optimisation to minimise both capital, operation cost and carbon dioxide emissions as multiple objectives. The latest work [123] studies a CHP-DH system and proposed multiregional coordinated planning and operation for such a system. The cost of conventional thermal generation and CHP generation is set as an objective for this multi-energy system. It takes the thermal inertia of the building and thermal comfort into consideration for the modelling. In terms of large scale CHP planning, the work in [124] discussed CCGT CHP planning considering primary energy savings as well as considering the present value of the CHP system depending on the type, age and operating condition. A further study on the application and cooperation of different types of energy with multi-criteria optimisation is performed on an industrial area [125]. According to different drivers of the model, different configuration and operation of the CHP system, centralised solar plant and thermal storage are optimised. Results on an indusial area show that solar plant coupled with optimal thermal storage allows reaching both environmental and economic goals.

To conclude, the objectives to be achieved for the optimal CHP planning and operation could be divided into four aspects. The first aspect is energy related with the primary goal to reduce the use of energy. The second aspect is considering the environmental impact which might include a various range of emissions such as CO_2, SO_2 and some other GHGs. The third part is cost-related objectives, which provides an economic signal to the CHP optimisation. Some of them would covert energy usage into energy cost or convert carbon emission into carbon cost, others would consider InC, operation and maintenance cost of the CHP system. The last aspect is integrating different goals into a multi-objective from the above-mentioned objectives. In this case, the objectives of different aspect are weighted in a single objective function.

It could be known that most of the CHP optimisations are focusing on the benefits brought the CHP solely, yet as energy converter in a multi-carrier energy system, the impacts of CHP to be brought to different energy vectors should be investigated, particularly the impact on the network capacity utilisation and the measurement to be taken to deal with such impact and how to convert the impact into a quantified indicator. This might not be as apparent as the energy cost or carbon reduction in the short term, but will have a profound influence on the planning and operation of the multi-carrier energy system in the long term.

2.5.2. CHP Models

The models of the CHP system are identical according to the types of energy vectors, the size of the networks and their application. A developed offline model for CCHP system is proposed in [126]. This CCHP system contains a CHP with an auxiliary boiler, absorption chiller, and heat storage unit to interact with electricity, thermal and cooling network. The optimal energy flows of each energy vectors are determined according to the changing energy price, in order to achieve a minimum energy cost in daily operation time. The study in [115, 116] explores CHP planning under uncertainty in two parts. The first part uses a multiple time frame approach that includes three-time frame: long-term time frame (years) is addressed by defining various scenario with large-scale uncertainty characteristic; medium-term time frame (within 1 year) uses Monte Carlo simulation to model the uncertainty like price and load variations; short-term time frame (monthly) is addressed by predefining notations and models for different energy vectors. The second part provides planning alternatives using decision theory-based assessment.

It also uses a pre-defined set of planning models for different energy alternatives and uses novel economic indicators like discount payback period and internal rate of return as planning objectives. Older work in [17] uses a stochastic model to perform the CHP generation simulation to meet the local demand. The probabilistic approach is based on two-dimensional probability load density functions. Relative research in [127] studies three different types of energy service as an alternative energy system in city level. Assumptions are made during the modelling that a CHP system and energy supply plant are available for every consumer.

Both static and dynamic models of the CHP system are presented in the above research depending on the temporal internals of the planning and operation methods. In general, short term operation such as daily analysis usually considers dynamic CHP model including generators, absorption chiller and heat recovery system, while long term schemes use the static model to represent input and output of the CHP system to integrate different energy vectors.

2.5.3. CHP in Energy Networks

As the interdependence of different energy infrastructure is becoming closer, CHP planning has been expended from a single network to multi-carrier energy system. The work in [128] studies the uncertainty impact of electricity price on the CHP operation of a multi-carrier energy system. A framework is proposed in this study to assess price impact. The energy flow and network modelling used per-unit form. The work in [129] investigates profitable alternatives like CHP and CCHP in a competitive multi-energy market. Energy vectors such as electricity, natural gas and demand for heating and cooling are included in the multi-scenario analysis to find the most convenient CHP solution with the electricity and gas price variations. In the same outlook, the work in [130] also investigates the financial performance to provide an optimal CHP plan and operation solution for a multi-carrier energy system. It presents a comprehensive model for the network and introduces cost and benefit analysis as an indicator to determine optimal plan and operation. Another multi-carrier energy system study [131] of the urban area shows the CHP planning is often subject to the restrictions of practical reasons. It uses the similar MILP as optimisation model to design city level multi-carrier energy system according to the city size and the included technology. An electricity-heating network [132] is supplied by a CHP-DH system. The authors model and optimise the CHP-DH system by minimising the overall costs of the network acquisition for heat and power in a deregulated power market. Another work in [133] also assesses the potential of CHP combining different energy infrastructures by considering network reliability, power loss and voltage profile. This multi-objective to obtain optimal size and site of CHP in a local energy system is realised by a genetic algorithm (GA) based solver called GAMS. The planning indicators in [134] are with the system reliability, energy efficiency and emission matrices to identify optimal planning schedules. The energy converter would be a CHP and a natural gas furnace. Another regional level of multi-carrier energy system work [135] provides a comprehensive and detailed model with various types of energy vectors and services. It evaluates a bioenergy system with integrated CHP plant and local biofuel transportation with the main driver to reduce transportation cost.

To summarise, with the increasing volume of DG and RE, the cooperation between CHP with these technologies are studied to interconnect multi-carrier energies. Hence it is vital to provide a comprehensive and detailed model of a different energy network such as electricity, gas and heating network.

2.6. Chapter Summary

This chapter firstly introduces the concept and planning strategy of the multi-carrier energy system and then benefits, developments of CHP as playing an important role in multi-carrier energy system is thereby reviewed.

The concept of the multi-carrier energy system is first introduced. This is categorised into four parts: spatial/geographical part in terms of the size of the system range from building to regionals, multi-service in terms of the multiple energy services to provide for users, multi-fuel in terms of the energy inputs, and networks in terms of different energy sectors to interact with each other through energy converter components. Afterwards, the planning and operation of the multi-carrier energy system are reviewed. A large number of existing optimisation methodologies of the multi-carrier energy system are reviewed. Different operation strategies are proposed according to the planning temporal horizon. The delivery of the performance of the proposed method is discussed either by directly providing absolute values or make convictive comparisons with reference values. The objective for planning methodology is particularly reviewed from energy, economic and environmental point of view.

This chapter also introduces CHP in the later content. The concept of a CHP system is firstly introduced, followed by the benefits, policies to incentivise CHP development in the UK. The operating principle of CHP is illustrated in terms of prime mover, the fuel selection, the electricity generator and the heat recovery system. A static state CHP modelling is introduced and will be modified and used in the later chapter. The importance of optimal CHP planning is addressed. A detailed review of CHP planning and operation with a great number of studies is divided into three perspectives: objectives, models and networks.

Chapter 3.

Identifying the Correlation between Temperature and Gas Consumption

THIS chapter discusses about the correlation between temperature and gas consumption in a local energy system, using a set of data processing techniques and demonstrates their correlation for different scenarios.

3.1. Introduction

In the modern energy market, the planning and operational decisions made by the network owners and suppliers, in terms of power generation, power transmission and power distribution and energy price/tariff design have been changing in order to meet the end-use demand [136]. Traditionally, most studies focused on the electricity energy network demand response schemes [137]. Nevertheless, other forms of energy have become important in the development of the interaction of multi-carrier energy system and natural gas is one of them which is playing a crucial role in the energy landscape. For example, in 2014, 278TWh of natural gas was consumed by domestic sector in the UK, which accounted for 63% of the UK's total domestic energy consumption, while electricity is only taking one-quarter of it. As introduced in the literature review, more customers are willing to have their energy vectors interacted with each other to provide the energy service with high efficiency using newly developed energy conversion and storage technologies such as DG and RE. Before interconnecting different energy sources and providing proper planning and operation of the energy enablers, it is necessary to study the pattern of different energy demand for customers. As many research has conducted methods to capture and model electricity demand [138-142], few mention the natural gas network. For the majority of the UK's domestic customers, natural gas is typically used for generating heat, which is closely related to the temperature and weather. This chapter aims to study how the temperature could affect the gas demand. This includes capturing the relationship between gas demand and temperature and determining the correlation between gas consumption and temperature in different time intervals.

In recent years, researchers start to explore the relationship between weather and gas consumption, but there are some drawbacks:

- First, in some studies, maximum gas demand and maximum temperature data are used as data inputs for modelling their relationship [143, 144]. Though the peak gas demand could be modelled and estimated through the temperate change, such models could not reflect normal energy consumption and its pattern against temperature apart from peak demand [145-147].
- Second, studies using hourly-resolution natural gas demand and temperature data will result in an inaccurate modelling method, particular for specific event or days that have an impact on the normal usage of gas for customers, resulting in a lower degree of the accuracy of their proposed models[148-151].

- Third, some literature took different types of gas demand such as industrial, commercial and local community into the consideration of demand-temperature sensitivity analysis [152]. The proposed modelling methods and results could only represent a very general idea of the relationship between gas consumption and temperature. A detailed mathematical model for different types of gas users with their correlation with weather and temperature should be given due to the energy patterns of different customers vary dramatically.

To tackle the problems and overcome the disadvantages revealed in previous research, a novel method to identify the correlation between gas consumption and the temperature is proposed in this chapter. A regression method is used for the gas-temperature data to be processed and qualified their correlation in a mathematical manner. An outlier detection technique is applied to the data set to exclude bad data. It calculates the Mahalanobis distance (M-distance) of each of the gas-temperature data to secure the authenticity of the data by defining outlier data that diverges far away from the main data group. This method by measuring M-distance is widely used in data processing such as data cluster analysis and classification and developing linear regression models. Different case studies have been carried out according to the different time period from annually to monthly and also study the difference between weekday/weekend and day/night. The real-time natural gas consumption and temperature data are collected from local energy system and local weather station.

The proposed method has the following merits compared with previous studies. Firstly, using the real-time data could be more reflective of the relationship between gas demand and temperature compared to that use peak values. The application of data detection and linear regression will ensure the data authenticity and provide correct correlation. The results conducted in this chapter will be divided according to the different time interval. Other factors such as customers’ behaviour will also be investigated to show how they will have an impact on the correlation between gas demand and temperature. Therefore the results in different scenarios are more representative compared to that disregard to such influence. This chapter provides convictive evidence of how temperature is correlated with gas consumption and use it as an important variable in the gas demand modelling and prediction in the future.

3.2. Methodology

This chapter introduces the techniques to be used to identify the correlation between gas consumption and temperature. An outlier detection method is used firstly to detect wrong data due to faulty, data absence or mismeasurement. It calculates an M-distance for each of the gas-temperature data pairs and compares it with the main group. An outlier could be identified and excluded from the rest of the data. After securing the authenticity of data, EMD is applied to the data and decomposes the data into several intrinsic mode functions (IMF). After this a linear regression is processed on this decomposed data, the most correlated part between gas consumption and temperature could be identified.

3.2.1. Outlier Detection

Outlier detection is required for a set of raw data. In statistics, outlier data is defined as the data that diverges greatly from the main data set [153]. This concept is introduced into this study to discover and exclude outlier data from the main data set to secure the authenticity of the data. In this study, statistical methods using M-distance is applied to identify the outliers [154]. M-distance measurement is primarily suitable for low-dimensional data set [155], therefore it is used in this study with 2-dimensional data consists of gas demand and temperature.

This M-distance measurement is to calculate the distance of a point and a distribution, which indicates the standard deviation of the point is away from the mean of the distribution. The expression of M-distance for an observation point could be defined as [154]:

$$D_M(\vec{x_i}) = \sqrt{(\vec{x_i} - \vec{\mu_i})^T S^{-1} (\vec{x_i} - \vec{\mu_i})} \quad \forall\, i = 1, \cdots, N \qquad \text{(Eq. 3-1)}$$

Where $\vec{x_i}$ is the i^{th} observation point, and $\vec{\mu_i}$ is the mean set and T is denoted for transpose matrix and S^{-1} is the inverse matrix of covariance matrix S. Covariance matrix is a matrix whose element in the i, j position is the covariance between the i^{th} and j^{th} elements of a random vector [156].

To classify if a test point is belonging to one of the data using the M-distance method, the value of the covariance matrix should be obtained. If the test point has a greater M-distance from rest of the sample population of the point, it could be defined as an outlier since it has a greater influence on the slope or coefficients of the regression equation [157].

In this case, the gas demand data and the temperature data are collected for a whole year in a half-hour time interval, each of them could be paired up at the same time to form a group of gas demand-temperature data set as an observation point $\vec{x_i}$ from 1 to N.

The M-distance for each gas-temperature data pair is identical to others without lower or upper limits. Outliers of this set of data are quantified as those observation points with relative great

M-distance compared with major data groups [158]. Sometimes errors, faulty data or mismeasurement might occur during the data collection of original gas consumption and temperature. Thus it is necessary to identify and exclude outlier data before further analysis is carried out. The process of identification and exclusion of bad data from the raw data set will significantly improve the quality and increase the accuracy of the following data processing.

3.2.2. Empirical Mode Decomposition

EMD is a process to break down a signal into various components. These components are described as IMF and they could form a complete and nearly orthogonal basis for the original data [159]. EMD process maintains the local characteristic of the data which make it a widely used process to deal with a nonlinear and non-stationary set of data [160].

The decomposed IMFs have two features: first, for the whole group of data, the total number of its extrema is either equal or differ at most by one to the number of the zero-crossings; second, the mean value of the upper and low envelopment of the function must equal to zero. These two requirements guarantee a well-behaved Hilbert transform of each decomposed functions. The procedure of EMD to extract IMF is also called shifting process using the following steps:

1. Spot all the local minimum and maximum of the data set;
2. Build the upper envelope (curve) for the data set by connecting all local maximum with a cubic spline line interpolation [161];
3. Build the lower envelope for the data set by connecting all local minimum with a cubic spline interpolation.

As the upper and lower envelopes of the data have covered all data between them, the mean curve between the two envelopes is defined as m_1. The first IMF could therefore be calculated as:

$$X(t) - m_1 = h_1 \qquad \text{(Eq. 4-2)}$$

Where $X(t)$ is the data set, and h_1 is the residue after the first IMF.

Ideally, this residue h_1 should also meet the requirement as the data set to be decomposed. By following the 3 steps above, the second IMF could also be produced:

$$h_1 - m_2 = h_2 \qquad \text{(Eq. 4-3)}$$

Where h_2 is the new residue after the second IMF.

After k^{th} iterations, when the h_{k+1} becomes a monotonic function where no more IMFs could be extracted using EMD, then process stopping criterion is satisfied. It is said the original data after the EMD process consists of k IMFs with a residue h_{k+1}.

3.2.3. Linear Regression

After the EMD process, both gas demand and temperature will be decomposed into a set of IMFs. Then each IMF of the same order for gas demand and temperature will be paired up again to calculate the correlation coefficient between them. Linear regression technique is introduced here to compute the correlation coefficient between gas and temperature IMF data. This correlation coefficient reflects the level of how gas demand corresponds to the temperature change. Linear regression is widely used for the analysis of the relationship between two sets of data.

The correlation coefficient r between data set X and Y is defined as the covariance of two variables divided by their standard deviations respectively, which is expressed by [162]:

$$r_{x,y} = corr(X,Y) = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y} \quad \text{(Eq. 4-4)}$$

Where $cov(X,Y)$ is the covariance of data set (X,Y), E is the expectation and σ_X and σ_Y are the standard deviation of X and Y, respectively.

To simplify the calculation of correlation coefficient, Pearson's correlation coefficient is applied and represented by [163]:

$$r_{x,y} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad \text{(Eq. 4-4)}$$

Where n is the size of data set x and y, x_i and y_i refers to the i^{th} individual sample and $\overline{x}$ and $\overline{y}$ are the mean for data set x and y, respectively.

Table 3-1 shows the range of the correlation coefficient and its meaning.

Table 3-1. Level of Correlation Coefficient

$\lvert r_{x,y} \rvert$ Range	Demonstration
1	Perfectly positive or negative linear correlation
0	No correlation
$(0, 0.3]$	Barely linear correlation
$(0.3, 0.5]$	Weakly linear correlation
$(0.5, 0.7]$	Moderately linear correlation
$(0.7, 1)$	Strongly linear correlation

As the gas demand and temperature data have been decomposed into several IMFs, thus serval correlation coefficients could be obtained from each pair of IMFs, the final correlation coefficient is defined as the average value of all correlation coefficient value from each IMF except residues.

3.2.4. Implementation Procedure

Figure 3-1 shows the flowchart and the main steps to implement the proposed methodology.

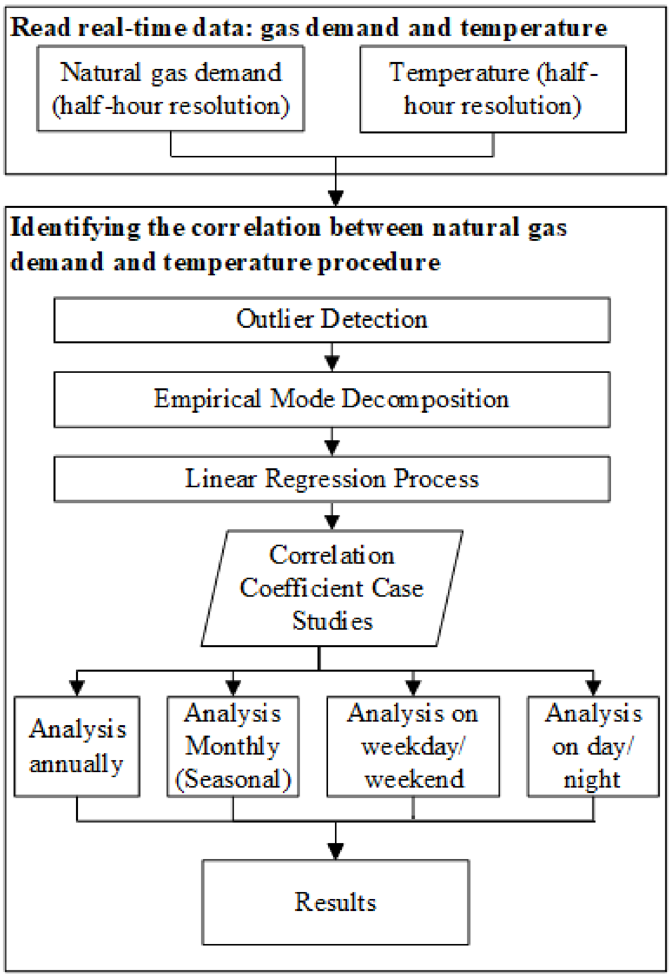

Figure 3-1. Flowchart of the Proposed Method

- Import half-hourly gas demand and temperature data for a year time as input data.
- Apply outlier detection by measuring M-distance for each gas-temperature data pair, identify and exclude outliers from the main data group.
- Apply EMD as data processing technique on both gas and temperature data to obtain IMFs.
- Using linear regression processing to calculate the correlation coefficient for different scenarios from long term annually to short term monthly, other cases are also conducted

to investigate different gas-temperature correlation patterns and identify the difference for weekday/weekend and day/night.

3.3. Case Study

In this subchapter, different case studies are presented to demonstrate the results of the proposed method according to time intervals of the data. The content of the case studies is organised as follows:

- Chapter 3.3.1 shows the results of applied outlier detection by measuring M-distance of each gas demand-temperature data pair. Outliers with relatively high M-distance from the raw data are identified and removed from it.
- Chapter 3.3.2 shows the results of applying EMD process on the data and discuss how it could improve the correlation between gas and temperature by comparing with original data without EMD process.
- Chapter 3.3.3 and 3.3.4 present the correlation identification between gas consumption and temperature in both long-term and short-term perspectives.
- Chapter 3.3.5 and 3.3.6 discuss the situation from another point of view. The first part investigates the correlation difference between weekday and weekend and the second part investigates the difference between day time and night time.
- Chapter 3.37 is to examine the effectiveness of the proposed method using another network data of a different country.

In this research, the gas consumption data is collected starting from August 2011 to July 2012 for a year in 30 minutes resolution from the University of Bath in the UK, the weather and temperature data of the same time period is collected from local weather station Paul Wilman Bath Weather [164] and Weather Underground [165]. Daily total gas consumption and daily average temperature are calculated based on the raw data collection.

3.3.1. Outlier Detection Application

Using the method introduced in the methodology section, the M-distance for each of the gas-temperature data pair is shown in Figure 3-2.

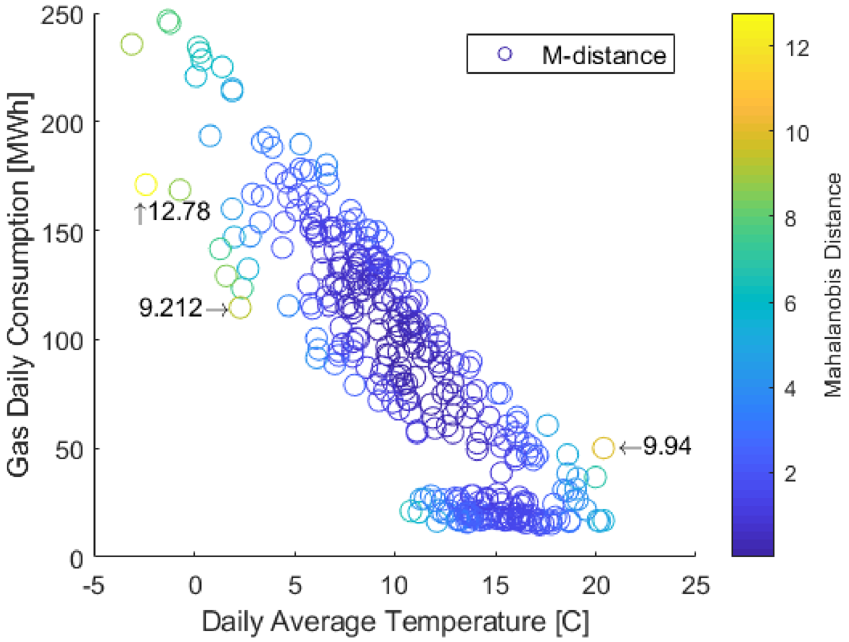

Figure 3-2. M-Distance of the Gas-Temperature Data for the Whole Year

In Figure 3-2, the colour bar on the right hand side shows the value of M-distance in different colour levels. M-distance increases gradually from dark blue to green then to yellow. The average M-distance of the whole data set is measured as 1.994. There are three noticeable gas-temperature data pairs with relatively higher M-distance against others. The one with highest M-distance is of the yellow circle in the figure with an M-distance value of 12.78. The physical meaning of this gas-temperature data pair is 171MWh daily gas consumption at -2.4℃, which is abnormal as rest of the gas consumption value at this temperature level is usually around 250MWh. The second highest M-distance gas-temperature data pair is at around 20℃ with 50 MWh gas consumption, its M-distance is 9.94. Given the fact that all other gas consumptions at 20℃ are generally around 10 to 20 MWh. The third outlier to be identified is with M-distance of 9.212 at around 7.5℃ with a relatively low gas consumption of 110MWh, while for most of the gas consumption around this temperature is much higher.

By applying outlier detection technique of measuring M-distance for each data pair and comparing it with the main data group, raw data are filtered and wrong data has been excluded from it due to wrong record and misreading. This secures the data authenticity and will therefore increase the accuracy and validity of the following process to obtain the correlation between gas and temperature.

3.3.2. EMD Data Processing

The EMD processing will shift the original data into a series of IMFs with a residue. Using August's daily gas consumption and average temperature data to make an example of showing how this process is done.

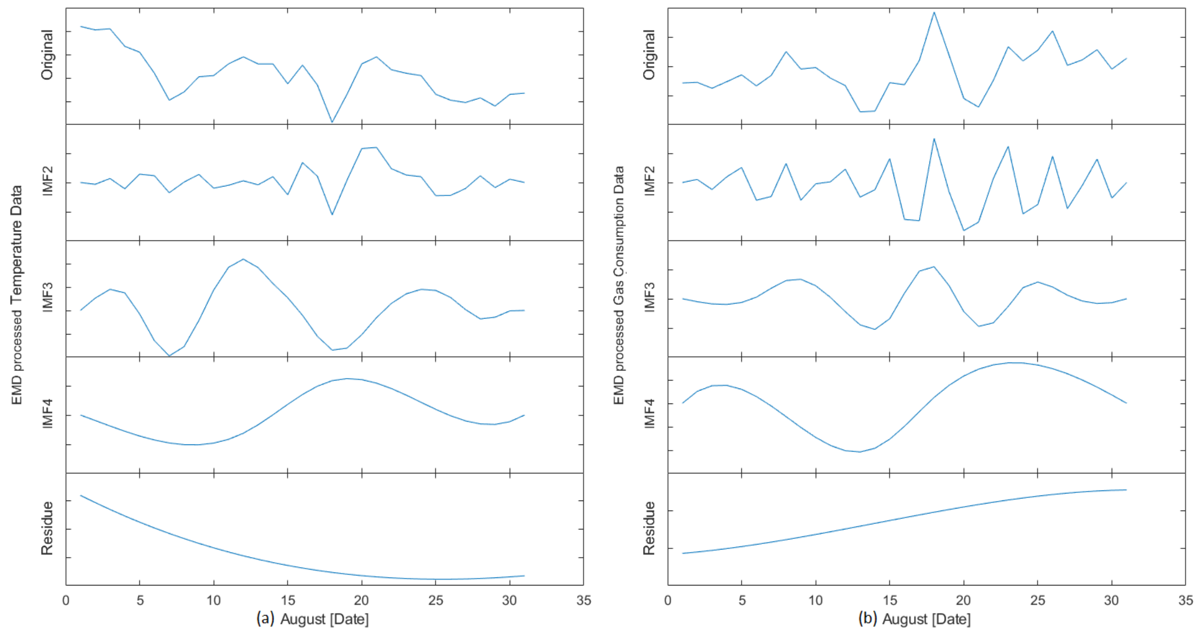

Figure 3-3. Data after EMD: (a) Temperature Data (b) Gas Consumption Data.

In Figure 3-3, it is seen that both original temperature data and gas consumption data have been decomposed into three IMFs with a monotonic residue. Figure 3-3(a) is the temperature data with its respective IMFs in a different order and a residue and Figure 3-3(b) is the gas consumption data with its IMFs and a residue. IMFs and residue of each data set could compose into the original data. IMFs of gas consumption and temperature in the same order are used to obtain a correlation coefficient. The final correlation coefficient could therefore be calculated. Compare it with the coefficient before applying EMD process to identify the correlation change between gas demand and temperature.

3.3.3. Annually Correlation Change

In this case, long-term gas consumption correlation with temperature is analysed for a year time frame. Figure 3-4 shows the data of daily gas consumption and daily average temperature after removing outliers.

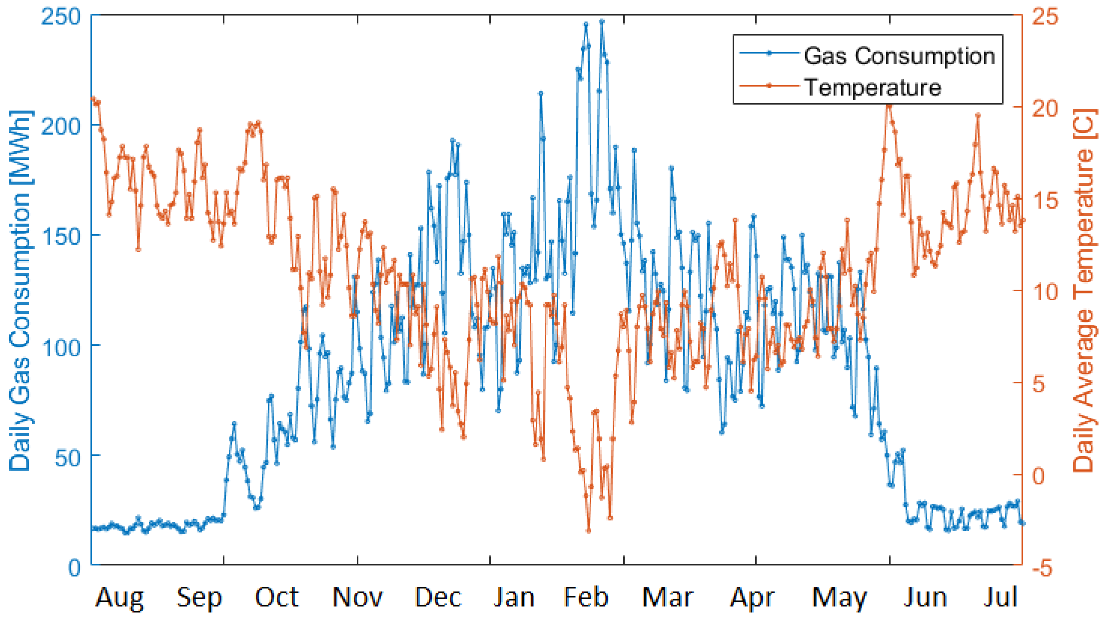

Figure 3-4. Annual Gas Consumption and Temperature Data Curve

In Figure 3-4 the blue curve represents the daily gas consumption and the corresponding daily average temperature is represented by the orange curve. These two curves show a general trend of how gas consumption is changing with the temperature. When the temperature level is high from August to September and next June to July, the gas consumption hasn't changed too much. With the weather gets colder, the gas consumption increases significantly from October to February at its highest level. As the spring comes and the temperature begins to rise, gas consumption drops again.

The gas and temperature correlation coefficient before and after the EMD process is calculated using a linear regression technique and the results are shown in Table 3-2. It could be observed from this table that the long-term (annually) correlation coefficient before applying EMD is -0.8819, which have already indicated a strong correlation between the gas consumption and temperature. By using EMD on the data set, the correlation coefficient between gas consumption and the temperature is -0.9241, indicating a further correlation is found between these two variables. Results give the reader an indicator of understating the impact of temperature on gas consumption in the long term time scale.

Table 3-2. Annual Correlation Coefficient

Correlation Coefficient before EMD	Correlation Coefficient after EMD
-0.8819	-0.9241

3.3.4. Seasonally Correlation Change

Although long-term analysis could present a general view of how gas consumption is correlated with temperature, it cannot reflect the seasonal influence of the weather. Thus a short-term case study is conducted to investigate such influence. The time interval is scaled down to a monthly basis. Typical month weather of each of the seasonal is selected and the gas consumption with temperature curve is shown in Figure 3-5.

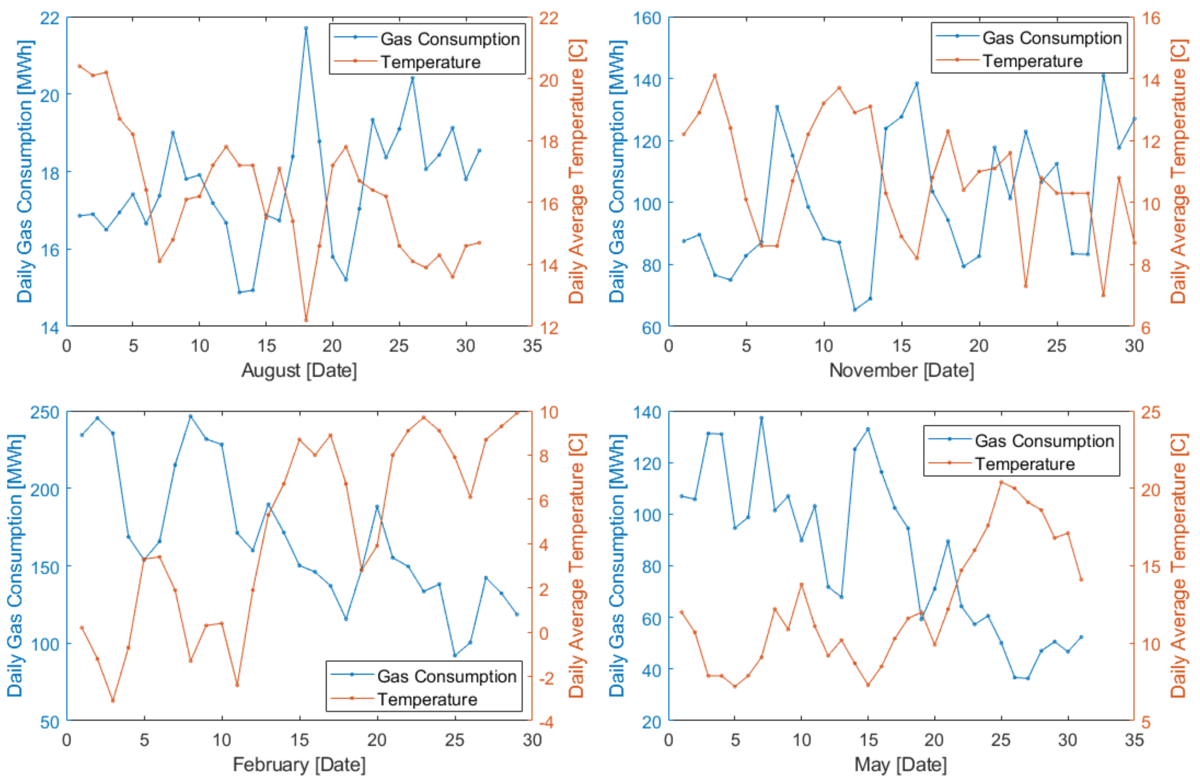

Figure 3-5. Seasonal Gas Consumption and Temperature Data Curve

The average temperatures of these four months are 16.2℃, 10.8℃, 4.5℃ and 12 ℃ respectively, which could typically represent the temperature level for four seasons in the UK. From all four figures above, it could be observed that despite some fluctuation of the gas-temperature data, the general change of the daily gas consumption (blue curve) is in the opposite direction of the temperature (orange curve), no matter it is summer time in August or the coldest February in the winter.

To verify this change, linear regression is applied to the data before and after the EMD process and results are shown in Table 3-3. According to the coefficient margins in Table 4-1, there is a moderate linear correlation between the gas and temperature in August before using EMD. And this coefficient is increased to -0.920 after applying EMD. Compared with other seasons, the correlation coefficient between gas consumption and temperature in summer (2011.08) is lower than that of other seasons no matter before (with a value of -0.684) or after (with a value of -0.920) using EMD process. As the weather of this month is the hottest, it could be known that the relatively high-temperature level will reduce the correlation between gas consumption and temperature.

As for the autumn and spring, they share the same weather conditions according to the monthly average temperature. The results in Table 3-3 show that they have the similar correlation between gas and temperature before EMD with respective values of -0.721 and -0.776, as well as after EMD process that are increased to -0.937 and 0.938, respectively. By comparing their situation with that of the summer, the colder weather has strengthened impact from temperature to gas consumption.

Among four seasons, the results show the strongest correlation between gas consumption and the temperature is revealed in winter. The data in February has the illustrated the most obvious correlation with a coefficient of -0.831 of the original data set and increased to -0.941 after EMD process. As the average temperature during this month is 4.5℃, gas demand is huge due to the support for the heating system. Thus, the regression sensitivity of gas is significantly affected by the temperature at this level.

Table 3-3. Monthly Correlation Coefficient

Time Period	Correlation Coefficient before EMD	Correlation Coefficient after EMD
Summer (2011.08)	-0.684	-0.920
Autumn (2011.11)	-0.721	-0.937
Winter (2012.02)	-0.831	-0.941
Spring (2012.05)	-0.776	-0.938

3.3.5. Correlation Change during Weekday and Weekend

In this subchapter, the correlation change is analysed from another point of view by investigating the impact from different customer behaviours on weekdays and weekends. Thus the gas consumption temperature data pairs are divided into weekdays and weekends. The curve of daily gas consumption and the daily average temperature from February's data are shown in Figure 3-6.

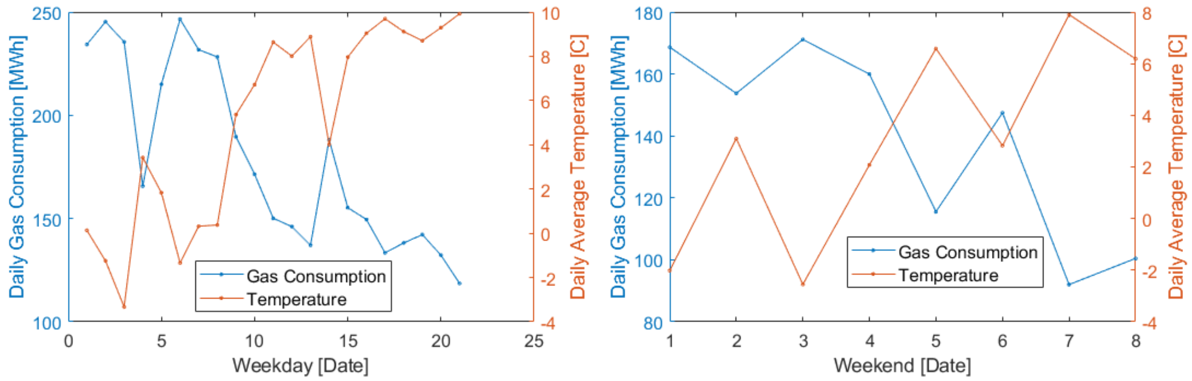

Figure 3-6. Weekday and Weekend Gas Consumption and Temperature Data Curve

The average temperature of the weekday's data and that of weekend's data are 5.0℃ and 3.0℃. Therefore, they are about the same on temperature level. In both curves in Figure 3-6, a very strong negative regression relationship between gas consumption and temperature could be identified. With the temperature increases or decreases, the gas consumption changes in the opposite direction.

To calculate the correlation coefficient between these two sets of data, EMD and linear regression technique are applied to the data and the results for the correlation of weekday and weekend are shown in Table 3-4.

Table 3-4. Weekday and Weekend Correlation Coefficient

Time Period	Correlation Coefficient before EMD	Correlation Coefficient after EMD
February	-0.831	-0.941
Weekdays	-0.9694	-0.9993
Weekends	-0.9267	-0.9960

Compared with the whole February's correlation coefficient between gas consumption and temperature of -0.831, the division of data into weekdays and weekends has increased the relationship between daily gas consumption and daily average temperature stronger. The weekday's correlation efficient is -0.9694 before EMD process and that of the weekends is -0.9267. These results indicate by separating the data according to weekday and weekend, the gas consumed by the customer share the same pattern according to the different customer behaviours in working days and holidays, resulting in increased correlation coefficient in respective time slots compared with that without dividing the data in weekday/weekend category.

Once EMD is applied to the data, the correlation coefficient has been further increased. For weekday case, this correlation coefficient has negatively increased from -0.9694 to -0.9993, which already represents a strong correlation is found between gas consumption and temperature. For weekend case, the correlation coefficient has also negatively increased from -0.9267 to -0.9960.

The results in this case study could be concluded that the daily gas consumption is becoming much more sensitive to the daily average temperature by splitting the data set into weekdays and weekends according to different customer's behaviours. This has shown evidence that besides temperature as a primary factor to affect gas consumption, different human/customer activity patterns will also have a significant influence on the use of gas. Another case study to investigate customer's impact on gas usage is analysed in the next subchapter.

3.3.6. Correlation Change during Day and Night

This section will focus on the correlation study during day and night. This day time is defined as from 08:00 am in the morning to 20:00 pm in the early night and the rest time of a day is defined as night time. The definition of day time and night time is according to the working time during the day and the time for people to go home. The curve of the gas consumption and temperature during day and night of the data in February are shown in Figure 3-7.

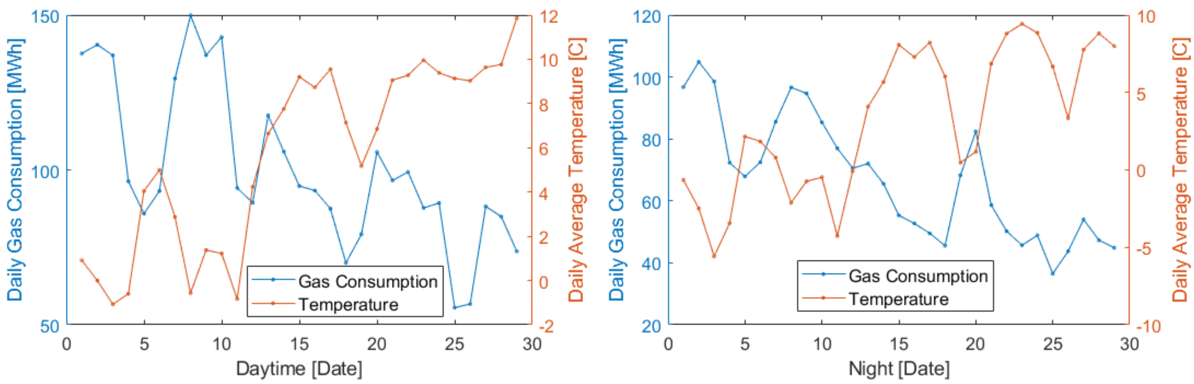

Figure 3-7. Day and Night Gas Consumption and Temperature Data Curve

The average temperature data of all day time from 08:00 to 20:00 is 5.7℃ and that of the night time is 3.3℃. A very small temperature level difference which could be neglected. The gas consumption during the day time in February varies greatly from day to day, from as high as nearly 150MWh to low as 50MWh, while the temperature difference is only around 10℃. The gas consumption change during the night during this month is much gentler. The biggest difference is around 60MWh while the biggest temperature change is over 15℃.

This result shows that gas consumption during the day time is more sensitive to the change in temperature. However, this change is not linear with the change of the temperature. As for the night time, the amount of gas consumption changes less that than during the day even if the temperature has varied greatly. But its gas consumption is more temperature-sensitivity and is more linear regressed to the temperature.

The results of the EMD process of the day time and night gas consumption and temperature data are shown in Table 3-5.

Table 3-5. Day Time and Night Time Correlation Coefficient

Time period	Correlation Coefficient before EMD	Correlation Coefficient after EMD
All day	-0.831	-0.941
Day	-0.6994	-0.8464
Night	-0.8491	-0.9634

Compared with the results before separating the data into day time and night time without EMD progress, the correlation coefficient during the day is changed from -0.831 to -0.6994, which also proves the analysis for the day time data curve in Figure 3-7. This change indicates that the correlation between gas consumption and temperature during the day time is reduced to a less correlation level. As for the night time, the correlation coefficient has a slight negative increase from -0.831 to -0.8491, which reveals a more correlated relationship is found between gas consumption and temperature at night.

The performance of EMD has increased the correlation between gas and temperature in terms of both day time and night time period. The results of day time are strengthened with a correlation coefficient change from -0.6994 to -0.8464, from moderate correlation level to a strong correlation level. Results during night time also find that such correlation is stronger after the EMD process with a correlation coefficient from -0.8491 to negatively increased to -0.9634.

This case study shows that the relationship between gas consumption and temperature has opposite results during the day and night. While the gas-temperature correlation is weakened during the day, it strengthens during the night. Considering that fact that data are collected from a university, which could be regarded as combination area of the residential and commercial sector, the human activity during day and night are therefore becoming an important factor to affect the gas consumption.

3.3.7. Correlation Analysis besides the Data in the UK

To verify the performance of the proposed method, another set of gas consumption and temperature data is used. The gas data is collected in May from an energy network in the Victoria area in Australia [166] and the temperature data is collected online [165]. The weather condition of Australia in the Southern Hemisphere of the Earth is very different from that in the UK. This is to validate the effectiveness of the proposed method to identify the correlation between gas consumption and temperature to be used at other places. The curve of the daily gas consumption and daily average temperature are shown in Figure 3-8.

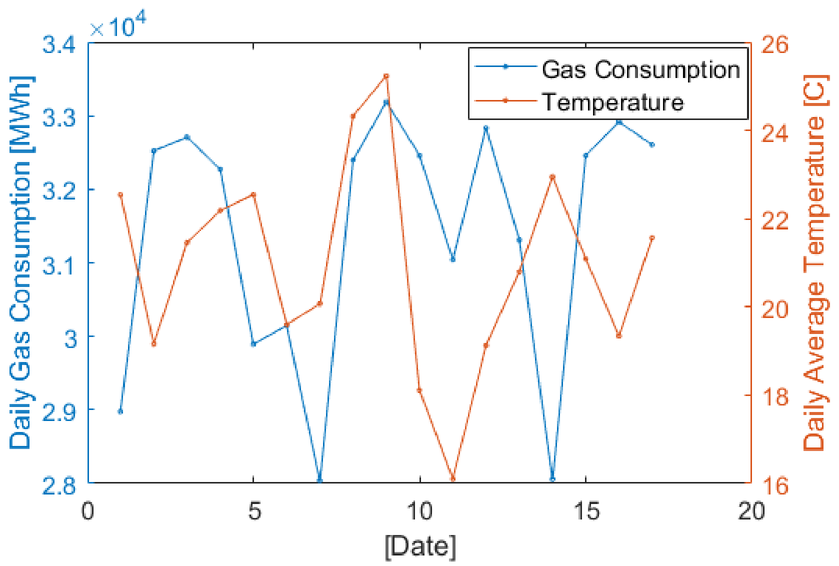

Figure 3-8. Consumption and Temperature Data Curve of Victoria, Australia

From the original curve of gas and temperature data it could be observed that in general, with the temperature changes, the gas consumption will change in the inverse direction. However, an exception is shown from day 6 to day 9. This could result in a lower correlation coefficient between gas consumption and temperature data.

Table 3-6. Correlation Coefficient of the Data of Victoria, Australia

Data	Correlation Coefficient before EMD	Correlation Coefficient after EMD
Victoria, Australia	-0.731	-0.958

The correlation before and after applying EMD to the data is shown in Table 3-6. It could be known that this coefficient is -0.731 before applying EMD process. Due to the fact that the local energy network is a large industrial sector with a local gas consumption of around 31,000MWh on daily basis and the temperature level is quite high at around 21℃, the correlation between gas and temperature is therefore not strong. With the application of EMD process, this correlation coefficient is increased to -0.958. It could be conducted that the proposed method using outlier detection, EMD and linear regression have managed to identify the temperature sensitive part of the gas consumption with other data set. The proposed method is not only valid locally but also valid for other places.

3.4. Chapter Summary

This chapter proposes a method to identify the correlation between gas consumption and temperature by using a combination of outlier detection, data processing technique and linear regression. The use of outlier detection is based on the measurement of M-distance, which is used as a criterion to locate and exclude bad data from the original data set. The data processing technique uses EMD to split the original gas consumption data and temperature data into several IMFs and a residue. At last, the application of calculating the correlation coefficient between the pre-processed gas-temperature data is used to obtain a quantified index to reflect how the gas consumption is related to the temperature. The features and main contributions of the study in this chapter are summarised as follows:

- Using the outlier detection, data processing technique and linear regression are proven to be effective to identify the correlation between gas consumption and temperature. The results in this study are important as convictive evidence to use temperature as a critical factor and variable to be used in the gas demand modelling and prediction.
- Different scenarios are conducted to illustrate how gas consumption is affected by the temperature level. From a long term perspective, the temperature is more correlated with gas consumption. From a short term perspective, this correlation is weakened due to the temperature level. Customer activity will also affect the correlation between gas and temperature from the weekday/weekend and day/night studies.

To conclude, the proposed method in this chapter presents a clear view of how gas demand is affected by temperature, which is critical to study gas load characteristic and have potential to be the base of modelling gas load. With the cooperation of all the electricity demand prediction studies, integrated energy loads could be modelled to provide future demand and to be used in the optimal planning and operation of a multi-carrier energy system.

Chapter 4.

Optimal CHP Planning Considering Future Network Investment Cost

THIS chapter proposes a model to optimally plan CHP considering future network investment. A LRIC matrix and IC are designed as objectives to find optimal site and size of CHP in different cases.

4.1. Introduction

Cogeneration or CHP is a process to generate electricity and heat at the same time in a highly efficient manner. It could capture the wasted heat during the production of electricity and use it for space/water heating. Compared to the conventional power plant and boiler, it has a relatively high efficiency of 80% to 90% [124]. CHP could also provide the following benefits: first, it can reduce carbon emission by up to 30% compared with conventional electricity and heating generation methods such as power station and heating boiler; second, CHP can offer energy savings of around 20% less than typical electricity and gas energy customers according to [167], third, CHP users could benefit themselves by selling electricity back to local grid. CHP could also help in the decentralisation of network construction and ease the tense of the growing transmission utilisation and reduce power loss during the transmission and distribution.

With the increasing penetration of on-site CHP in the UK, there is growing attention on the optimal planning and operation of CHP. The central topic on CHP planning not includes on reducing energy cost compared with traditional energy generations, but also includes on reducing carbon emission to combat greenhouse effects. All these objectives have added difficulties on CHP network planning with regards to system security and reliability[168].

Most of the research activities aim to optimise CHP planning using the following optimisation criteria, such as energy cost reduction, energy savings maximisation, carbon emission minimisation or reduction of the cost of carbon emission. A few research managed to pursue an overall goal among some of the objectives simultaneously by making the compromise of some. Therefore several optimisation criteria and optimisation problem modelling and solvers have been proposed to obtain the optimal site and size of CHP in the electricity network.

Limited researches have been conducted to investigate the influence of CHP on the distribution network future investment, which is encountered by most network operators. Moreover, with the further penetration of CHPs, their employment will have an impact on the network users to pay charges, which is passed by the network suppliers. Network charge is a form of the charge against network users for their use of a network. Generally, the main objective of the network charge is to recover the network capital cost, network operation and maintenance cost. Network charge could also provide to the network owners with a piece of forward-planning, economic-efficient information to show the utilisation of networks [169]. Optimal planning of CHPs could significantly benefit the network operators in terms of redirected power flows and reduced transmission utilisation and deferral of future network components investment. Therefore, it could also benefit network users to reduce their network charges.

In the UK, all network users are required to pay UoS charges to use the network. Power suppliers purchase electricity from generation companies on behalf of network users and customers, these suppliers are charged by the network operators, who deliver energy to customers. And suppliers pass these charges to customers in terms of the UoS charges. Statistics show that in the UK, network charges are accounted for 13%-15% of the overall bill for a typical network customer [170]. According to the network characteristics, the charging methodology is various in different industry codes. For electricity network, it is categorised by the levels of the network system. For a typical high voltage level transmission network, the network charge uses InC related pricing for charge calculation [171]. For a low-voltage distribution network, the distribution reinforcement model pricing method from Ofgem [172] is developed to tackle the network charging issues. Long run marginal cost [173] and LRIC [19, 174] are another two typical network pricing methodologies for the distribution network. For the natural gas network, the charging methodology is comprised of two parts: transmission and distribution. Traditional transmission gas network pricing is introduced in [175]. Transmission network charging includes capacity charge, interconnection point charge, commodity charge and other charges. Gas distribution network (GDN) charge is also called local distribution zone charge. It provides the network operator with a price control and an indicator to recovery their revenue and pass this cost to the network users. It reflects the cost, facilitates competition and reflects the developments of GDN business [176]. About 80% of the gas network charges are coming from the GDN charges. In recent year, the development DERs, particularly the penetration of CHP in the UK's market have a significant influence on the planning of various energy sectors, proper planning for the interaction between different energy networks will be profound, as CHP would change the supply, demand and power flow among these networks. It will also affect the network maintenance and future investment. From this point of view, CHP is playing a more and more important role in the multi-carrier energy system, by affecting the network operator's decision making on future network investment, which also leads to the UoS charges for the network users.

This chapter proposes a novel method for planning CHP in distribution network considering network investment and UoS charges. An LRIC matrix is proposed to determine the optimal site of CHP and total IC is used as an object to determine the optimal size of CHP. LRIC is a pricing method that makes use of the unused capacity of an existing network to reflect the cost of advancing or deferring future investment consequent upon the addition of generation or lead at each study node, proposed in [19]. The proposed model in this chapter is resolved by a non-linear optimisation approach using interior-point solver.

The main contribution of this chapter is that: first, it designs a novel LRIC metric to quantify how unit sized CHP have an impact on the distribution network in terms of future network InC; second, it proposes a new investment-oriented sizing model for CHP in order to minimise network component cost and network charges; third, it points out that the reduction on future investment of network components provides a forward-planning signal to inform the future CHP employment strategies.

4.2. The Proposed Model

As the main goal of this chapter is to determine the optimal location and capacity of the CHPs to be employed in a distribution network, in order to minimise the future InC and consequently minimise network charges, a two-stage solution is proposed. The schematic plan of the proposed method is shown in Figure 4-1.

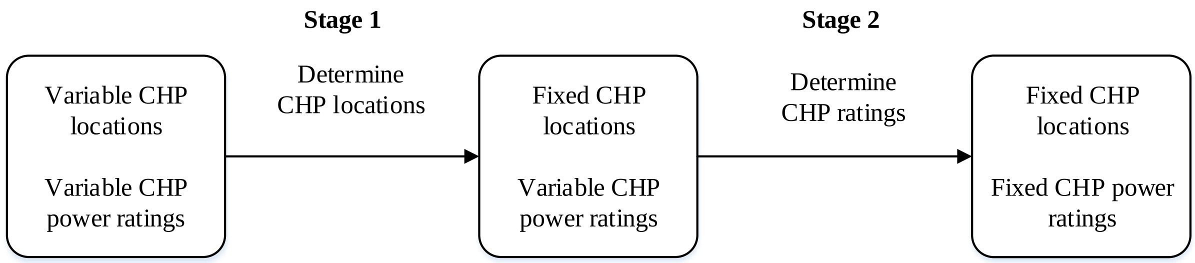

Figure 4-1. Two-Stage Method for Optimal CHP Planning

Stage 1: In the first stage, the assumption is made that a unit-sized CHP is employed at each bus of the network once at a time, therefore the impact of CHP could be measured at each bus. The objective of this stage is to obtain the optimal bus to install CHP and the benefit it could provide to the system in terms of the deferral of the future investment of network transmission lines and the reduction on the future InC. Network charges in terms of this future investment could be calculated every time a unit-sized CHP is placed at each bus. When all buses are done placing unit-sized CHP hypothetically, an LRIC matrix could be obtained. For those buses with relatively negative higher LRIC value, it indicates that these buses with CHP employed have the potential to reduce more network future reinforcement investment and hence reduce more on network charges. For single CHP planning, the top choice for optimal CHP location would be the bus with the lowest negative LRIC value. For multiple CHPs planning, the optimal buses would be those with LRIC value in descending order.

Stage 2: In the second stage, the objective is to determine the optimal size of CHP to provide the whole electricity network with lowest total IC. With CHP/CHPs deemed to be at the determined site/sites which are done in Stage 1, objective function is achieved using an interior point solver. Both proposed stages are processed within the constraints of formulating the electricity network, such as power flow balance, bus voltage limits and power capacity of lines. Capacity limits are also applied to CHPs for practical reasons [177].

4.3. CHP Location Selection

This section presents the proposed method of the first stage, which is to optimally locate the site for CHP in an electricity network considering its impact on network future InC and network charges. An LRIC matrix is built in order to introduce the potential of each bus by placing a unit sized CHP to reduce network charges for users. This matrix is calculated by hypothetically placing a unit-sized CHP at each bus once at a time and obtain the change of the total network IC. As stated in Stage 1, the bus with negatively higher LRIC value would be the better site to install CHP.

The LRIC matrix index is defined as:

$$I_{LRIC} = \begin{pmatrix} LRIC_1 \\ \vdots \\ LRIC_m \\ \vdots \\ LRIC_M \end{pmatrix} \qquad \text{(Eq. 4-1)}$$

Where m is the m^{th} bus in a M-bus network, $LRIC_m$ is the LRIC under the assumption of unit-sized CHP placed at m^{th} bus. $LRIC_m$ is calculated by the following steps.

4.3.1. The Present Value of the Network Components

For an electricity network consists of M bus and N lines, each line, for example, line n between bus i and bus j, has its individual capacity C_n to support a power flow of P_n. With the growth of the demand, the power flow of each line will grow as well, assuming a power flow growth rate (GR) per year of line n is g_n, then for this line n, it will take a number of years y_n for the current power flow P_n to reach to its own power capacity C_n, this is expressed by:

$$C_n = P_n \times (1 + g_n)^{y_n} \qquad \text{(Eq. 4-2)}$$

Rearranging this expression and it will become:

$$(1 + g_n)^{y_n} = \frac{C_n}{P_n} \qquad \text{(Eq. 4-3)}$$

Taking the logarithm of both side of this equation and rearranging it, the value of years to take to reach line capacity, y_n, could be calculated:

$$y_n = \frac{\log C_n - \log P_n}{\log(1 + g_n)} \qquad \text{(Eq. 4-4)}$$

Under this circumstance, it is reasonable to assume that after y_n in the future, with the demand grows, the power flow on line n will reach its capacity C_n. Therefore, line reinforcement will be taken place by adding an transmission line of same configuration to meet the growing demand.

4.3.2. The Present Value of Future Investment Cost

The future investment of this new line could be expressed by the current line asset value (AV) $AV_n$and its discount rate (DR) d_n and the time to reach full power capacity y_n. For simplicity, it could be expressed by the following equation:

$$PV_n = \frac{AV_n}{(1 + d_n)^{y_n}} \qquad \text{(Eq. 4-5)}$$

Where PV_n is the present value of the future investment of network line n.

4.3.3. The Difference of Present Value with Unit Size CHP Installed at Bus m

Assuming that there is a unit size 1MW CHP installed at bus m, it will cause the power flow change along with all the lines in the system. In this situation, the power flow on line n will become to a new value PV_new_n and consequently, its time horizon for future reinforcement using the same line growth rate will change from y_n to y_new_n. This could be expressed as:

$$C_n = P\_new_n \times (1 + g_n)^{y\_new_n} \qquad \text{(Eq. 4-6)}$$

Where P_new_n is the new power flow due to unit size CHP installed at bus m.

The new reinforcement year to take place could be calculated using the same method by rearranging the equation and taking the logarithm:

$$y\_new_n = \frac{\log C_n - \log P\_new_n}{\log(1 + g_n)} \qquad \text{(Eq. 4-7)}$$

And the new present value of the future investment of this line n will become:

$$PV\_new_n = \frac{AV_n}{(1 + d_n)^{y\_new_n}} \qquad \text{(Eq. 4-8)}$$

Now, the difference between the present value of the investment of network component line n before and after having unit size CHP installed at bus m could be calculated:

$$\Delta PV_n = PV\_new_n - PV_n \qquad \text{(Eq. 4-9)}$$

If the value of ΔPV_n is positive, it indicates that the installing CHP increases power flow than it is without installing CHP, the future reinforcement horizon has been advanced. If the value of ΔPV_n is negative, it means that installing CHP benefits this line by reducing its current power flow, deferring the future reinforcement horizon and essentially reducing the cost for future line investment that is passed to network users to pay in terms of network charges.

4.3.4. LRIC of all Lines with Unit Size CHP Installed at Bus m

Annuity Factor (AF) is introduced here in order to reflect the time value of money. Time value of money is the concept that the amount of money received in a future date is generally worth less than if the same amount of money is received today. This factor describes the influence of time on asset value and in this research, the reinforcement investment will take place in a future day, therefore is important to consider it into the modelling. For line n, it is expressed by[178]:

$$AF_n = \frac{1 - (1 + d_n)^{-LS_n}}{d_n} \qquad \text{(Eq. 4-10)}$$

Where LS_n is the life span (LS) of network line n.

The result from dividing ΔPV_n by AF_n could actually represent the change of future InC change of network line n. By adding up all this value of each network line from 1 to N and divided by the unit size of the installed CHP at bus m, the LRIC value for a potential location bus m for CHP employment could be obtained:

$$LRIC_m = \frac{\left(\sum_{n=1}^{N} \frac{\Delta PV_n}{AF_n}\right)}{1MW} \qquad \text{(Eq. 4-11)}$$

By placing unit size CHP once at a time at each bus, each value of the LRIC matrix in Equation. 4-1 could be obtained. According to Equation. 4-2 to Equation. 4-11, the change of each LRIC is caused by the power flow change in each network lines, which is eventually caused by the unit size CHP injection at each bus. LRIC matrix index I_{LRIC} is thus able to show an overview of how a presumptive CHP at each bus could have an influence on the future network investment and change the network charges. Optimal CHP site could therefore be selected according to the LRIC matrix index. If the buses are with negatively higher LRIC value, it indicates they are suitable to be the location to install CHP by deferring future reinforcement horizon, reducing future network investment and consequently reducing network charges for customers.

4.4. CHP Sizing

This section introduces the formulation of optimal CHP sizing. The objective of CHP sizing is to minimise the total future InC for the network lines. The objective function of optimal CHP sizing is modelled as:

$$\min IC(P_n^{CHP}) = \min \sum_{n=1}^{N} \frac{\Delta PV_n(P_n^{CHP})}{AF_n} \qquad \text{(Eq. 4-12)}$$

ΔPV_n and AF_n are calculated using the same process by Equation. 4-2 to Equation. 4-10, except that the power flow change P_new_n in Equation. 5-8 caused by the CHP injection is not in unit size at certain bus but by single or multiple CHPs with variable size from different bus locations according to the number required from the previous section. This objective function is able to not only show the power flow change along the network branches, but more importantly, capture the economic-beneficial signal for the system branches, which could reflect how much CHPs could bring down future network lines investment with proper CHP sizes.

For practical reason, the maximum active output of CHP for a distribution network is generally no larger than 50MW, which is considered fit for the case study network system in this chapter. For different network systems, CHP capacity could be altered to accommodate different levels of planning requirements. In this case, the CHP size should be subject to the following constraints:

$$\begin{cases} P_{n,min}^{CHP} \le P_n^{CHP} \le P_{n,min}^{CHP} \\ Q_{n,min}^{CHP} \le Q_n^{CHP} \le Q_{n,min}^{CHP} \end{cases} \quad \forall\, n = 1, \cdots, N \qquad \text{(Eq. 4-13)}$$

Where P_n^{CHP} and Q_n^{CHP} are the active and reactive power output of CHP location at bus n, $P_{n,min}^{CHP}$ and $P_{n,max}^{CHP}$ are its active minimum and maximum power limits, $Q_{n,min}^{CHP}$ and $Q_{n,max}^{CHP}$ are its reactive minimum and maximum power limits, respectively.

4.5. Electricity Network Formulation

Electricity network is formulated based on the power flow on the transmission line and the power balance at bus [179].

4.5.1. Power Flow Formulation

For an electricity network with M buses and N branches, the power flow on the n^{th} branch from bus i to bus j could be formulated using the following expression [179]:

$$\begin{cases} P_n = P_{ij} = V_i^2 \left(\dfrac{G_{ij}}{a^2} + G_{sh} \right) - \dfrac{V_i V_j}{a} \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \\ Q_n = Q_{ij} = -V_i^2 \left(\dfrac{B_{ij}}{a^2} + G_{sh} \right) - \dfrac{V_i V_j}{a} \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) \end{cases} \quad \forall \begin{matrix} i,j = 1,\cdots,M \\ n = 1,\cdots,n \end{matrix} \qquad \text{(Eq. 4-14)}$$

Where P_n and Q_n are the active and relative power flow on branch n, P_{ij} and Q_{ij} indicate the active and reactive power flow between bus i and bus j, V_i and V_j is the magnitudes of the voltage of bus i and bus j respectively, θ_{ij} is the voltage angel difference of between bus i and bus j, G_{ij}, B_{ij} and $G_{sh}$are the conductance, susceptance and shunt admittance between bus i and bus j, a is the transformer tap ratio between two buses.

4.5.2. Bus Power Balance

The overall power should be in balance at each bus, which indicates that the power injection and power generation into the bus should be equal to the outgoing power and load at the bus. This applies to both active and reactive power. The relationship of the power balance is formulated using the following expression [179]:

$$\begin{cases} \Delta P_i = P_i^{Gen} - P_i^{Load} - P_i^{Flow} = 0 \\ \Delta Q_i = Q_i^{Gen} - Q_i^{Load} - Q_i^{Flow} = 0 \end{cases} \quad \forall \quad i = 1,\cdots,M \tag{Eq. 4-15}$$

Where ΔP and ΔQ are the active and reactive power difference, P^{Gen} and Q^{Gen} are the active and reactive power generation at this bus, P^{Load} and Q^{Load} are the active and reactive power load at the same bus and P^{Flow} and Q^{Flow} are the total power flow from other buses of the network.

Total active and reactive power flow at bus i from other buses could be calculated using the following expression:

$$\begin{cases} P_i^{Flow} = \sum_{j=1}^{M,j\neq i} P_{ij} \\ Q_i^{Flow} = \sum_{j=1}^{M,j\neq i} Q_{ij} \end{cases} \quad \forall \quad i = 1,\cdots,M \tag{Eq. 4-16}$$

If the value of P_i^{Flow} and Q_i^{Flow} is positive, it indicates that the overall power flow from other buses to bus i is outgoing, otherwise the overall power flow from other buses to but i is injected.

4.5.3. Electricity Network Constraints

There are some practical constraints of the electricity network to maintain system security and reliability. Firstly, the magnitude of bus voltage should be limited within 0.94 and 1.06 times of the reference voltage value [180], which is expressed as:

$$V_m^{min} \leq V_m \leq V_m^{max} \quad \forall\, m = 1,\cdots,M \tag{Eq. 4-17}$$

Generally, every line in the electricity network would have its own power flow capacity to restrain the maximum power flow and remain secure:

$$\begin{cases} -P_n^{Capa} = P_n = P_n^{Capa} \\ -Q_n^{Capa} = Q_n = Q_n^{Capa} \end{cases} \quad \forall \quad n = 1,\cdots,N \qquad \text{(Eq. 4-18)}$$

Where P_n^{Capa} and Q_n^{Capa} is the active and reactive power ratings of branch n.

4.6. Implementation Steps

The flowchart for implementing the proposed method is shown in Figure 4-2.

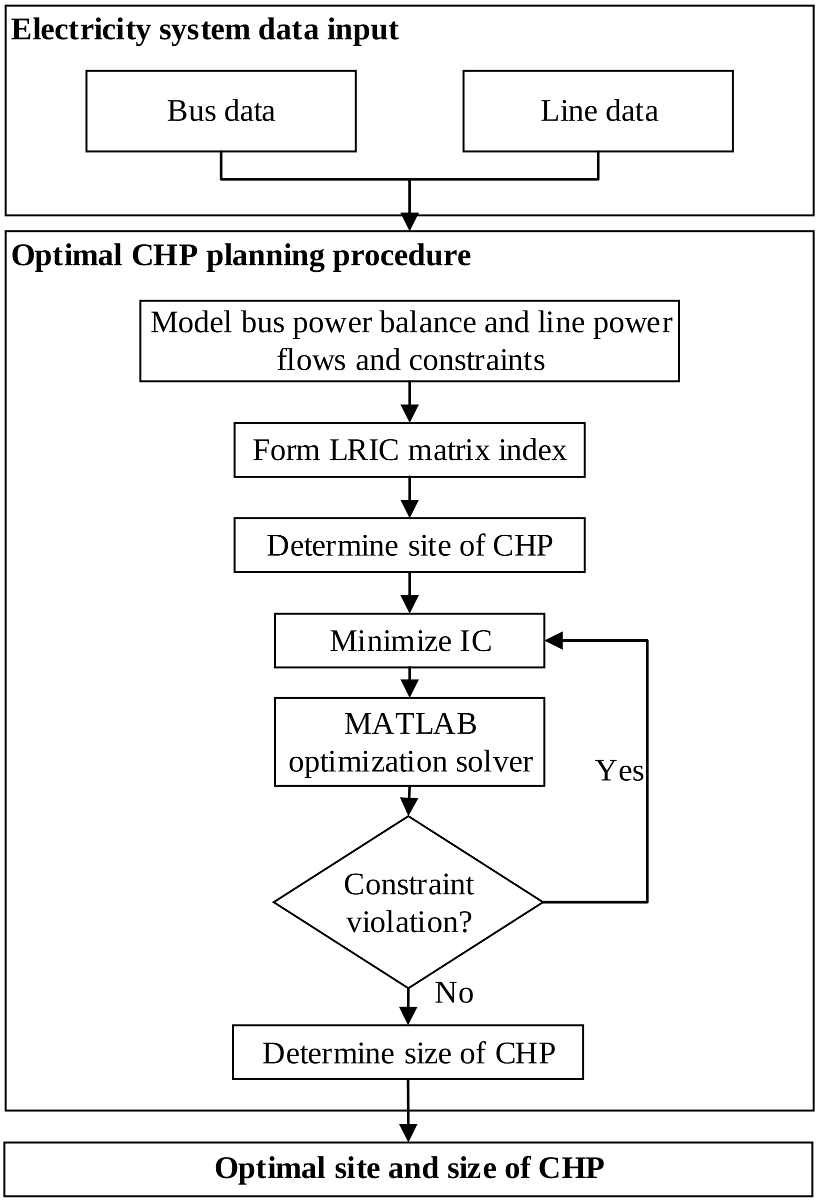

Figure 4-2. Flow Chart of Optimal CHP Planning

1) Read electricity network data including bus data and branch data as program inputs.

2) Formulate bus power balance, line power flow and network constraints of equations Equation. 4-14 to Equation. 4-18, and model them in MATLAB.
3) Formulate the equations Equation. 4-1 to Equation. 4-11 for CHP siting. Calculate the LRIC matrix index by hypothetically placing a unit size CHP at each bus once at a time.
4) According to the results of the LRIC matrix, select the location for optimal CHP planning using the following criterion. The bus with negatively highest LRIC value indicates that it has the potential to minimise the future InC for system owners and hence reduce the cost that is passed to the customers that pay in network charges. Once the number of CHPs to be planned is confirmed, the optimal locations for CHP are the buses with LRIC value in a negatively descending order.
5) Formulate the equations Equation. 4-12 and Equation. 4-13 for CHP sizing.
6) Use the interior point solver in MATLAB to solve the optimisation problem to minimise the total IC.
7) Continue the process and check the process that any of the constraints is violated. A global optimum will be obtained after iterations with all system constraints met.

4.7. Demonstration on a Two-Bus Network

This section implements the proposed method on a single two-bus system with a CHP installed at the demand side, shown in Figure 4-3.

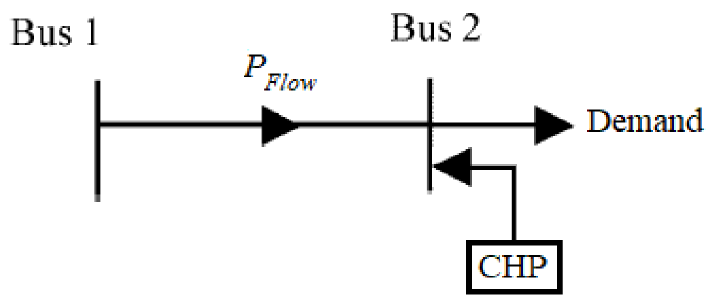

Figure 4-3. Simple Two-Busbar Network with Demand and CHP Injection

Bus 1 is a reference bus and bus 2 is a load bus with a demand of 30 MW. A CHP is installed at bus 2. The branch data is shown in Table 4-1. By gradually increasing the CHP output from 0 MW to 30 MW, the change in the branch utilisation, future reinforcement horizon, the results of differences between the present value of future InC and the IC could be observed in Table 4-2.

Table 4-1. Two-Bus System Branch Data

R	X	B	Capacity	GR	AV	DR	LS
0.001 pu	0	0	30 MW	5%	£3 m	10%	80 years

Table 4-2. Results of CHP Installed at Bus 2

CHP Size (MW)	Line Utilisation (%)	Reinforcement Horizon (year)	PV of Future Investment (£M)	IC (£M)
0	100%	0	3	0
5	83.3%	3.7	2.101	-0.090
10	66.7%	8.3	1.359	-0.164
15	50%	14.2	0.775	-0.223
20	33.3%	22.5	0.351	-0.265
25	16.7%	36.7	0.091	-0.291
29	3.33%	69.7	0.004	-0.300

In this two bus system with a CHP installed at the demand side, the output of CHP is adjustable in order to observe how its output change could have an influence on the system line and its future InC. It is clear that as CHP installed at the demand side, with the increase of CHP output, the load at bus 2 will require less power injection from the reference bus through the transmission lines between them. The results of the 2 bus system demonstration are shown in Table 4-2. The trend could be seen that with the increase of the CHP output, the branch power flow utilisation is decreased, the future reinforcement horizon has been significantly deferred from 0 years (CHP at idle) to 69.7 years (CHP at 29MW output). And also with a huge reduction on the present value of the future investment of the branch. When CHP is idle, the transmission line between the reference bus and the load bus is fully utilised and requires an imminent reinforcement to be taken place.

Another noticeable point from this table is that when CHP output is at 29 MW, which means it could almost fully supply load at bus 2. It defers the branch future reinforcement to 69.7 years by reducing the IC of £0.3M compared with the situation without CHP. This 2-bus network demonstration reveals the optimal CHP planning could have a far-reach influence on the network in terms of the network line future investment.

4.8. Case Study

The electricity network used in this chapter is a practical distribution network shown in Figure 4-4. The detailed network branch data and bus data are shown in Appendix A-1 and A-2, respectively. This distribution network is composed of 15 buses, 21 branches with 6 loads and an on-site fixed-output micro generator. A branch DR of 6.9% is taken for all network branches, which is commonly accepted Minimum Acceptable Rate of Return by the UK's distribution network operators. A load GR of 1.6% per year is taken, which is from the project long-term investment statement in the UK [181]. Three different scenarios are performed in this section: the first scenario is a single CHP optimal planning; the second scenario is multiple CHPs optimal planning; the third scenario is a sensitivity analysis to evaluate how the proposed method is performed with the impact of changing demand.

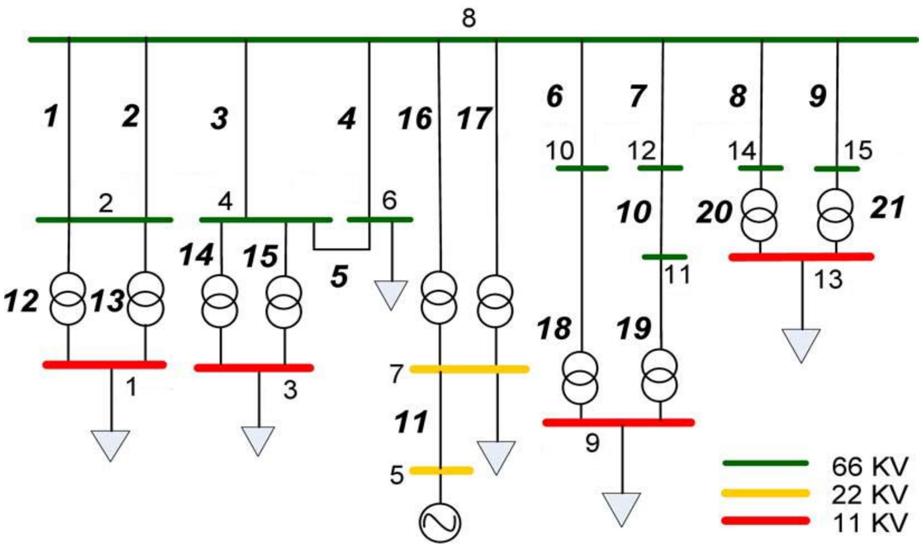

Figure 4-4. A Diagram of 15 Bus Practical Distribution Network from the UK

All three case studies are based on the two-stage planning method mentioned in chapter 4.2. The first stage is to determine the optimal site to install CHP. By placing a unit size CHP at every bus once at a time, an LRIC matrix could be obtained. According to the results of the LRIC matrix, the bus with negatively higher LRIC value is considered to be a better location to install CHP. If multiple CHPs are required, the sites for them are chosen from the buses of LRIC value in a negatively descending order. The second step is to determine the optimal size for the chosen CHPs from the first stage. This is achieved by obtaining the optimum to minimise the future network branch InC using interior point solver.

4.8.1. Single CHP Planning

This scenario considering single CHP optimal planning in the system described in Figure 4-4.

1) Optimal Site

Detailed LRIC matrix value for all buses by processing the first stage of the proposed method could be found in Table 4-3.

Table 4-3. LRIC Matrix for 15 Bus Electricity Network

Line \ Bus	1	2	3	4	5	6	7	9	10	11	12	13	14	15
1	-237	4,542	1	1	1	1	1	1	1	1	1	1	1	1
2	-8	-8	-1,981	3,863	-8	-5,638	-8	-8	-8	-8	-8	-8	-8	-8
3	-7	-7	-1,690	-556	-7	1,768	-7	-7	-7	-7	-7	-7	-7	-7
4	0	0	-10	-18	0	-9	0	0	0	0	0	0	0	0
5	-234	8,397	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	-68	69	-139	-137	0	0	0
7	28	28	28	28	28	28	28	-2766	4,854	4,642	4,141	28	28	28
8	0	0	0	0	0	0	0	-16	-28	9	57	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	2	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	4
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	-275	104	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
13	-273	106	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
14	-1	-1	-146	0	-1	0	-1	-1	-1	-1	-1	-1	-1	-1
15	1	1	-136	3	1	3	1	1	1	1	1	1	1	1
16	2	2	2	2	-292	2	-300	2	2	2	2	2	2	2
17	2	2	2	2	-218	2	-225	2	2	2	2	2	2	2
18	0	0	0	0	0	0	0	-11	23	-22	-21	0	0	0
19	0	0	0	0	0	0	0	-6	-10	30	29	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	1	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	1
LRIC (£/MW)	-1,002	13,167	-3,936	3,321	-499	-3,847	-514	-2,881	4,854	4,508	4,056	14	17	19

From Table 4-3, it could be seen that the optimal site to install single CHP would be bus 3, with an LRIC value of -3,936 £/MW. This indicates that bus 3 has the potential to reduce the total future InC by £3,936 per MW. Among this -3,936 £/MW at bus 3 with a unit size CHP installed hypothetically, -1,981 £/MW of it is from branch 2 from bus 8 to bus 2, and -1,690 £/MW of it is reduced from the future network investment from branch 3 from bus 8 to bus 4.

There is also some slightly future InC reduction on branch 14 and 15 with a value of -146 and -136 £/MW, respectively. Besides bus 3, there are also some other good choices to installed CHP such as bus 6 and bus 9 with an LRIC value of -3,847 £/MW and -2,881 £/MW. Another interesting point that could be found from Table 4-5 is that there are some positive LRIC value of some buses, revealing the fact that some buses might increase the overall line future InC if CHPs are installed at those buses. For example, bus 2 has the highest positive LRIC value of 13,166 £/MW, mainly consist of 4,542 £/MW on branch 1 from bus 8 to bus 2 and 8,397 £/MW on branch 5 from bus 4 to bus 6. This bus may potentially increase the network future InC if CHP is located at it. There are some other buses with positive LRIC like bus 4 and bus 10 to bus 15.

In this scenario, as single CHP planning is considered, therefore the bus with lowest LRIC value would be the optimal location to installed CHP, which is bus 3 with an LRIC value of -3,936 £/MW.

2) Optimal Size

The size of the single CHP optimal planning at bus 3 is determined by minimising the total IC using the second stage of the proposed method. The results are shown in Table 4-4.

Table 4-4. Results of Single CHP Optimal Planning

Site (Bus)		Size (MW)	
3		33.72	
Line No	Utilisation Change (%)	Reinforcement Horizon Change (year)	IC (£)
1	0	0	1
2	-53.3%	111.3	-19,877
3	-52.9%	104.5	-17,174
4	1.8%	-4.9	17
5	0	0	0
6	0	0	0
7	0	0	28
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	-3
13	0	0	-2
14	-36.5%	106	-1,038
15	-36%	105.9	-982

16	0	0	2
17	0	0	2
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
	-8.4% (Average)	20.1 (Average)	-39,026 (Total)

The single CHP optimal planning result of using the proposed method of the second stage and solving it with optimisation solvers is sized the CHP at 33.72 MW, with a total IC reduction of -£39,026. With this optimal CHP output, there is a significant power flow reduction on several lines. The power utilisation on line 2, 3, 14 and 15 have dropped by 53.3%, 52.9%, 36.5% and 36% respectively. Though there is a slight power flow utilisation increased by 1.8% on line 4, the average line utilisation of the whole network has been reduced by 8.4%. Another change of the network lines is their future reinforcement horizon, mainly reflect on line 2, 3, 14 and 15. Their line future reinforcement horizons have been deferred by 111.3, 104.5, 106 and 105.9 years, separately. Leading to 20.1 years of deferral of all system branch on average. As for the objective in this section, with single CHP generating 33.72 MW power, located at bus 3, the whole network line IC is -£39,026. In practice, CHP is not able to be sized with a decimal part, therefore the size of the CHP at bus 3 is selected at 34 MW in an integer.

In the distribution system, the maximum size of CHP output is usually at 50 MW for practical reasons. If a CHP is selected at bus 3 and changing its size from 0 to 50 MW, the influence of this CHP on network line future IC could be obtained, which is shown in Table 4-5.

Table 4-5. Results with Changing CHP Size from 0 to 50 MW

	Average Line Utilisation (%)	Average Reinforcement Horizon (year)	
Without CHP	32.6	94.8	
With CHP (MW)	Utilisation Change (%)	Horizon Change (year)	Total IC (£)
1	-0.4	0.6	-3,936
5	-1.8	3.1	-16,807
10	-3.7	7.2	-27,395
20	-6.8	15.6	-36,882
30	-8.7	25.7	-38,942
34	-8.4	20.0	-39,026
40	-8.0	25.8	-38,856
50	-4.8	8.9	-37,514

Before installing CHP into the system, the line power utilisation is 32.6% on average and 94.8 years on average of their future reinforcement. By placing CHP at bus 3 and increasing its output from 0 to 50 MW. Different changes are revealing on line utilisation, reinforcement horizon and total IC. Line power flow utilisation is decreasing with the growth of CHP output and reach its peak dropping point at 30 MW of -8.7% on average, then it gradually increased slightly and freeze-framed at -4.8% at 50 MW. As for the reinforcement horizon, it is deferring with the rising CHP size from 0 to 30 MW, which is 25.7 years at 30 MW. Then it advanced a few from that value to 20 years at 34 MW and deferred again to 25.8 years at 40 MW. At maximum CHP output of 50 MW, it only defers future reinforcement by 8.9 years than that without CHP in the system. The total IC is decreasing rapidly with the growth of CHP output and reached its minimum at 34 MW with a value of -£39,026, which is the optimum for the objective for single CHP planning. Then it slightly increased by £1,500 when CHP hit the maximum limited size of 50 MW.

An interesting point is that the changing trend of line power flow utilisation, future reinforcement horizon and total network IC do not cope with each other. With the changing size of CHP from 0 to 50 MW, the peak line utilisation drop point does not come with the minimum network IC. When CHP is sized at 34 MW, it comes with the objective of optimisation, but average network utilisation has passed its peak drop point. And the deferral line reinforcement horizon has experience rise and fall when CHP output is changing from 30 to 50 MW.

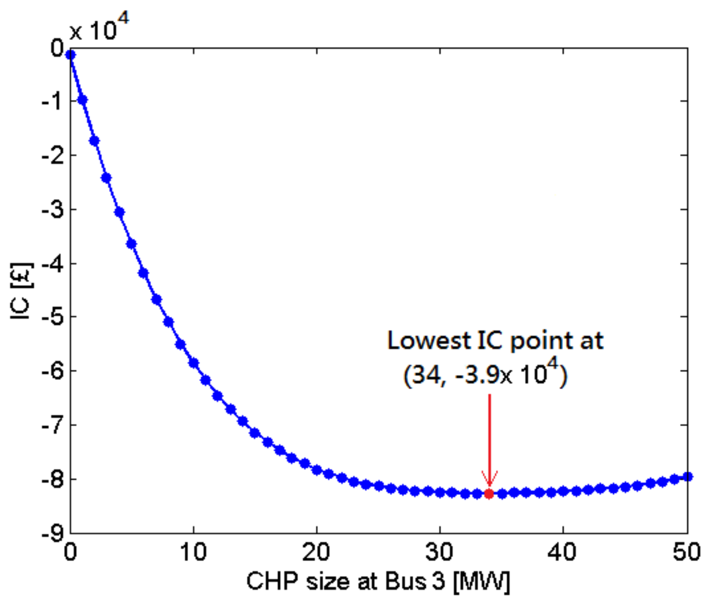

Figure 4-5. CHP Changing Size at Bus 3 against IC

Figure 4-5 shows the curve of a changing size CHP in integer located at bus 3 against the total IC it caused to the system. It could be observed from the figure that the total IC drops rapidly with CHP size is increasing at the beginning. After about 25 MW that CHP is injecting into the network, this trend becomes mild. The optimal size is at 34 MW when the lowest IC is reached. After this point, with the increasing size of CHP, the total IC is increased by a very small amount. This figure is drawn from the results of CHP size increased in integer, it also gives a validation of the results obtained from the proposed method using interior point solver in MATLAB.

In summary, the optimal solution for single CHP planning in this 15 bus system is sited at bus 3 with a size of 34MW, the IC from this solution is -£39,026.

4.8.2. Multiple CHPs Planning

This scenario considering multiple CHPs optimal planning. In this case, it is assumed that 3 CHPs are planning to achieve minimum network IC.

1) Optimal Sites

According to the LRIC matrix results in Table 4-5, the optimal sites for CHPs to install is at bus 3, bus 6 and bus 9 with their respective LRIC value of -£3,936/MW, -£3,847/MW and -£2,881/MW. The potential impact of CHP on bus 3 in terms of network future investment has been specified in chapter 4.8.1. Bus 6 is also optimal to install CHP, among its LRIC value of -£3,847/MW, though £1,768/MW from line 3 seem to increase the network future InC, -£5,637/MW is from branch 2 which potentially reduce it by a great amount. The main contribution of LRIC on Bus 9 from line 7 with a value of -£2,766/MW, which is also a good site for CHP to be installed.

2) Optimal Sizes

By implementing the proposed method and using proper optimisation solver, the results of multiple CHPs sizing are shown in Table 4-6.

Table 4-6. Results of Multiple CHPs Optimal Planning

Site (Bus)	Size (MW)
3	28.9

6		13.9	
9		19.2	
Line No	Utilisation Change (%)	Reinforcement Horizon Change (year)	IC (£)
1	0	0	1
2	-60.1	172.6	-19,888
3	-62.0	187.9	-17,190
4	-20.3	144.6	-43
5	0	0	0
6	-15.1	68.6	-238
7	-45.0	82.7	-19,445
8	-17.5	85.8	-71
9	0	-0.1	0
10	0	0	0
11	0	0.2	0
12	0	0	-3
13	0	0	-2
14	-44.0	254.7	-1,039
15	-43.4	254.7	-983
16	0	0	2
17	0	0	2
18	-9.4	40.3	-32
19	-5.6	24.3	-17
20	0	-0.1	0
21	0	0	0
	-15.4 (Average)	62.7 (Average)	-58,946 (Total)

From Table 4-6, the optimal sizes of CHPs located at bus 3, 6 and 9 are 28.9, 13.9 and 19.2 MW, respectively, with a total future network IC of -£58,946. There are three main changes with CHP at optimal sizes. First is the power flow on lines. There is a significant change of power flow utilisation on line 2, 3, 7, 14 and 15, with a respective load utilisation reduction of 60.1%, 62%, 45%, 44% and 43.4%. There is also some slight utilisation drop on line 4, 6, 8, 18 and 19 from 5% to 20%. The second change would be the future reinforcement horizon deferral cause by the change of line power. The average line future reinforcement horizon has been deferred by 62.7 years. The last change is the objective to determine the optimal sizes of the CHPs, the total IC is -£58,946, mainly contributed by line 2, 3 and 7 with a respective value of -£19,888, -£17,190 and -£19,445.

In summary, the optimum of multiple CHP planning considering network future InC is locating CHPs at bus 3, 6 and 9 with the output of 28.9. 13.9 and 19.2 MW, resulting in a minimised network IC of -£58,946.

4.8.3. Sensitivity Analysis with Changing Load

This section conducts a sensitivity analysis to evaluate the performance of the proposed method under a load change situation. The demand of the15 bus network is normal time demand that is not representative of some extreme situations such as peak load hit the network. This sensitivity analysis presumes that peak load hits the distribution system with a 50% demand higher than usual. The optimal planning for multiple CHPs would have changed.

1) Optimal Sites

New LRIC matrix is required to determine the optimal sites for CHP to install, which is shown in Figure 4-7. Detailed LRIC matrix for sensitivity analysis on each of the branch is in Appendix A-3.

Table 4-7. LRIC Matrix for Sensitivity Analysis.

Bus No.	1	2	3	4	5
LRIC (£/MW)	-4,033	13,484	-16,531	8,438	-1,983
Bus No.	6	7	9	10	11
LRIC (£/MW)	-9,841	-2,011	-6,002	8,367	6,061
Bus No.	12	13	14	15	
LRIC (£/MW)	5,379	-72	-65	-60	

From Table 4-7, it is known that the optimal sites for CHPs are at bus 3, 6 and 9, with an LRIC value of -£16,531/MW, -£9,841/MW and -£6,002/MW, respectively. Though they are the same buses selected in the same priority in the previous study, their LRIC values have changed greatly due to the power flow change in the system lines.

2) Optimal Sizes

The results of the optimal sizes to be obtained are shown in Table 4-8.

Table 4-8. Results of Sensitivity Analysis

Site (Bus)		Size (MW)	
3		42	
6		20	
9		25	
Line No	Utilisation Change (%)	Reinforcement Horizon Change (year)	IC (£)
1	0	0	10
2	-90.6	172.8	-111,830
3	-95.1	214.1	-96,230
4	-32.9	216.7	-240
5	0	0	0
6	-24.8	93.1	-1,030
7	-59	94.7	-46,850
8	-27	108	-290
9	0	-0.1	0
10	0	0	0
11	0	-0.4	0
12	0	0	10
13	0	0	0
14	-66.4	268.9	-5,760
15	-65.5	268.9	-5,450
16	0	0	0
17	0	0	-10
18	-19.1	66.6	-170
19	-15.3	52.9	-120
20	0	-0.1	0
21	0	0	0
	-23.6 (Average)	74.1 (Average)	-267,960 (Total)

The optimal sizes of CHPs located at bus 3, 6 and 9 are 42MW, 20MW and 25MW, which results in a total IC of -£267,960. With the demand increased by 50%, power flows on lines would also rise greatly. However, as CHPs installed on site, their power generation effectively reduces the power flows in system lines. This could be observed from the power flow utilisation, which is reduced by 23.6% on average. To be noted that on line 2, 37, 14 and 15, there is a significant drop in their utilisation. These power flow drops also lead to a huge deferral on the line future reinforcement horizon by 74.1 years on average. Last but not least, the IC due to optimal CHP sizes is -£267,960, which mainly come from three lines, line 2, 3 and 7, with their contribution of -£111,830, -£96,230 and -£46,850, separately.

4.9. Chapter Summary

This chapter proposes a novel method to optimally plan CHP considering the network future InC and network charges in a distribution network. Network operators could have control of the CHP planning by reducing their total IC. Compared with most of the CHP planning research, which use energy cost, carbon emission cost, capital cost as planning criterion, this proposed method managed to tackle the CHP planning problem from another point of view by looking into CHP's contribution to effectively reduce the cost for future network line investment. This makes it theoretically and economically strong in the completion among other CHP planning studies. The features and main contributions of the research of this chapter could be summarised as follows:

- Using future network investment for network operators and network charges for customers as a forward-planning economic signal to optimise CHP planning. The economic benefits from this proposed method could be quantified using the LRIC concept.
- Different scenarios are conducted to determine the optimal site and size of CHP including single CHP planning, multiple CHPs planning and sensitivity analysis to evaluate how the proposed method is performing under a changing load. Outcomes from all cases are satisfying with global optimum to be found with a minimised the objective.
- Using the LRIC concept into the proposed method gives a forward-looking for the network owners to quantify the CHP's future financial impact on the system line utilisation and network investment.

To summarise, the novel proposed method in this chapter is in order to optimally planning CHP from a new aspect by looking into how CHP could have a positive impact on the electricity network. Using this idea that looking into the future economic benefit would also be meaningful in other distributed energy planning in the system.

Chapter 5.

Optimal CHP Planning in Multi-Carrier Energy System Considering IC

THIS chapter proposes a model to optimally plan CHP in an multi-carrier energy system considering IC. Formulation on natural gas network and its LRIC are built. Case studies are demonstrated in single and multiple CHPs planning.

5.1. Introduction

With the increasing penetration of gas-fired DG and the promising future of power-to-gas technology, the interdependence between the electricity network and the natural gas network has become stronger and stronger. With the rapid development and utilisation of high-efficiency CHP that functioned as the linkage between two energy systems, it will profoundly affect the planning, operation and trading in the multi-carrier energy systems.

CHP planning will not only deal with technical difficulties such as applicability, system reliability and security, but also consider its economic impact on the capital cost, energy cost reduction and carbon emission reduction, more importantly, focus on the forward-looking signals it could bring to the network, such as future network InC and network charges, which have influence on behaviour for both network owners and customers.

The literature on CHP planning for multi-carrier energy system in terms of their models, optimisation methods and criterions have been introduced in Chapter 2. Most of the recent research on CHP planning put their attention to the current change to be brought such as how CHP could reduce energy cost and how to reduce carbon emission, or a multi-objective to achieve both. This chapter further discusses how CHP planning could benefit multi-carrier energy system by reducing future network investment and therefore reduce network charges for system users, as an extension work from Chapter 4 which only considers electricity network. This chapter proposes a novel optimal planning model for CHPs for both electricity network and natural gas network in order to reduce the overall IC of a multi-carrier energy system. The proceeding steps are similar to that in Chapter 4. The LRIC matrix is redesigned to presents the economic signal for both the electricity network and natural gas network. The potential location for CHP installation would be the coupling point that links both networks. LRIC matrix could be divided into an electricity LRIC matrix and a gas LRIC matrix. Unlike the electricity network, the future reinforcement would not be adding a new line, instead, adding the compressor station to meet the gas demand. Optimal sites for CHP are determined by the coupling point with the lowest LRIC value comprised of both networks. Then minimising IC of the integrated network to obtain optimal sizes of CHPs. The proposed method is tested on a multi-carrier energy system with a 15 bus electricity network and a 12 node gas network. The performance of the proposed method in an electricity-natural gas local system is demonstrated in two case studies. A single CHP optimal planning could reduce the total IC of both networks by 42% while a multiple CHP optimal planning could further reduce this cost by 63%. It proves the effectiveness to benefit both the system operators by deferring their reinforcement horizon and the network users by reducing their UoS charges.

This optimal CHP planning in multi-carrier energy system will rise a range of interests of different parties. For energy providers, it could offer benefits by enabling energy beyond the conventional borders of single energy network. And the form of multiple networks enhanced competitiveness in the market. For distribution network operators, it increases its potential flexibility and could attract more customers to participate in their systems. For customers, the integration of different energy network and the conversion between different energies could increase the security of energy supply, for example, CHP is function as on-site generation for local consumption and could produce environmental-friendly heat to supply during cold periods.

The main contributions of the studies in this chapter are: 1) Providing a CHP optimal planning method for a multi-carrier energy system. 2) Proposing an improved LRIC index matrix to describe CHP impact for both electricity and natural gas networks. 3) An optimisation model considering multi-energy carrier system constraints with the use of CHP to benefit both network owners and users.

5.2. The Overview of the Proposed Method

The overview of the proposed method is similar to that in Chapter 4. It also uses a two-stage solution to respectively determine the optimal sites and sizes of the CHP in a multi-carrier energy system. The schematic of the two-stage method is shown in Figure 5-1.

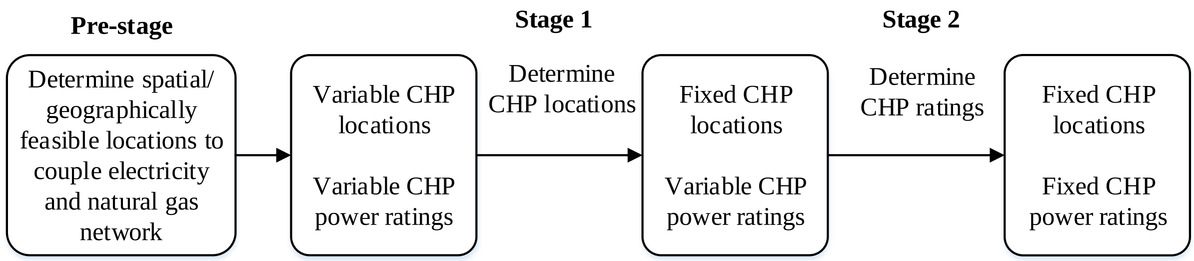

Figure 5-1. Schematic of Optimal CHP Planning for Multi-Carrier Energy System.

The objective of the optimal CHP planning is to minimise the overall network InC and by that to minimise the network charges for users of both electricity and natural gas network.

A pre-stage is added to identify the CHP coupling point between electricity and natural gas network that is geographically feasible. This is because the configurations of the electricity network and gas network are different from each other. Not every single bus in the electricity network could interact with every node in a natural gas network. The coupling point for CHP to operate as an interconnection must be the same location to have both electricity and gas demand.

Stage 1: this stage is to determine the optimal locations of CHPs in a multi-carrier energy system. In order to do that, an LRIC index matrix is proposed. It is an improved matrix based on the model in Chapter 4, which is derived by placing a unit size CHP at each coupling point between an electricity bus and a natural gas node, once at a time. It reveals the potential ability of a CHP system could benefit the multi-carrier energy system in terms of the InCs to be reduced. It could reflect the CHP’s economic impact for both energy network from network operators and users point of view. The optimal locations of CHP are chosen with the lowest LRIC values, which shows the lowest network investment to be paid in the future.

Stage 2: this stage is to determine the optimal capacities of CHPs in a multi-carrier energy system. In order to do that, an objective of minimising the total future network reinforcement investment is required. According to the locations picked from stage 1, this optimisation problem is formulated and solved in MATLAB using an interior-point based solver. Constraints and limitations are taking into consideration during the formulation of both energy networks.

5.3. CHP Location and Capacity Formulation

This section presents the methodology to optimally plan the multi-carrier energy system with CHP considering future network InC. Firstly, a modified LRIC index matrix is proposed as an indicator to show how each of the coupling points between electricity and the natural gas network could have the potential to benefit the network of installing CHP system. This is achieved by hypothetically locating a unit size CHP at each coupling point and calculate the LRIC value of both networks.

This LRIC index matrix, unlike the one in Chapter 4, is comprised of two parts, one is the LRIC value of the electricity network and the other is the LRIC value of the natural gas network. The coupling point with a negatively higher LRIC value means it has greater potential to reduce the total IC of both networks, it also indicates that it could further defer network reinforcement in the future and therefore reduce network charges. The LRIC index matrix I_{LRIC} is expressed as:

$$I_{LRIC} = \begin{pmatrix} LRIC_1 \\ \vdots \\ LRIC_x \\ \vdots \\ LRIC_X \end{pmatrix} \quad \text{(Eq. 5-1)}$$

Where x is the x^{th} coupling point that spatially feasible for a CHP system to interconnect electricity network with a natural gas network with a total number of X and $LRIC_x$ is the LRIC value of x^{th} coupling point.

$$LRIC_x = LRIC_x^E + LRIC_x^G \quad \text{(Eq. 5-2)}$$

To be practically feasible, this coupling point is the site to have both electricity and gas demand. $LRIC_x$ is the total LRIC value comprised of electricity LRIC value, denoted as $LRIC_x^E$ and natural gas LRIC value, denoted as $LRIC_x^G$. Each of them is calculated by the following steps.

5.3.1. LRIC of Electricity Network

This derivation of $LRIC_x^E$ is following the same process from Equation 4-2 to Equation4-11 in Chapter 4.3. Thus the electricity network LRIC for coupling point x could be represented by:

$$LRIC_x^E = \frac{\left(\sum_{n=1}^{N} \frac{\Delta PV_n^E}{AF_n^E}\right)}{E_{CHP}} \quad \text{(Eq. 5-3)}$$

Where ΔPV_n^E and AF_n^E are the difference between present value and annuity factor of the electricity network, respectively, and E_{CHP} is the electricity unit output of CHP.

According to the formulation described in Chapter 4.3, $LRIC_x^E$ is changing depending on the power injection into the electricity system from unit size CHP at coupling point x.

5.3.2. LRIC of Natural Gas Network

The formulation of LRIC of the natural gas network is similar to the process to formulate LRIC of the electricity network. The major difference is the calculation of the need for future network reinforcement. For the natural gas system, the gas flow along the pipeline is determined by the inlet and outlet gas pressure once the configurations of the pipeline such as pipeline length, diameter and thickness are fixed. However, the pressure drop through the pipeline is inevitable and therefore, the compression station will be required once the gas flow increase to cause the outlet pressure drop significantly. Compared with the electricity network adding new lines as future reinforcement measure, the measures of the natural gas network for future reinforcement to meet the increasing gas flow would be adding compressor station between the nodes.

For a natural gas network comprised of S nodes ad T pipelines, for example, pipeline t between node k and node l with a gas flow of q_t^G, its maximum gas flow, denoted as C_t^G would therefore calculated with its upper pressure limit and minimum pressure limit. Assuming that a gas flow growth rate g_t^G is applied to it, then it will take years y_t^G for the current gas flow q_t^G to reach to its own power capacity C_t^G, this is expressed by:

$$C_t^G = q_t^G \times (1 + g_t^G)^{y_t^G} \qquad \text{(Eq. 5-4)}$$

Rearranging this expression and it will become:

$$(1 + g_t^G)^{y_t^G} = \frac{C_t^G}{q_t^G} \qquad \text{(Eq. 5-5)}$$

Taking the logarithm of both side of this equation and rearranging it, the value of years to take to reach gas pipeline capacity, y_t^G, could be calculated:

$$y_t^G = \frac{\log C_t^G - \log q_t^G}{\log(1 + g_t^G)} \qquad \text{(Eq. 5-6)}$$

Under this circumstance, it is reasonable to assume that after y_t^G in the future, with the gas demand grows and the gas flow on pipeline t will reach its capacity C_t^G. Therefore, line reinforcement will be taken place, the compressor station will be needed to by adding a same line to ensure more demand could be met.

The future investment of this new compressor station could be expressed by the status quo line asset value $AV_t^G$and its discount rate d_t^G and the time to reach the year of reinforcement y_t^G. For simplicity, it could be expressed by the following equation:

$$PV_t^G = \frac{AV_t^G}{(1 + d_t^G)^{y_t^G}} \qquad \text{(Eq. 5-7)}$$

Where PV_t^G is the present value of the future investment of network pipeline t.

Assuming the installation of CHP with a unit gas injection G_{CHP} installed at node k, it will cause the new gas flow change along with all the lines in the system. In this situation the new gas flow $q\_new_t^G$ on pipeline t will affect the time horizon for future reinforcement from y_t^G to $y\_new_t^G$, using the same measures, it could be expressed as:

$$y\_new_t^G = \frac{\log C_t^G - \log q\_new_t^G}{\log(1 + g_t^G)} \qquad \text{(Eq. 5-8)}$$

Similarly, the new present value of the future investment of network pipeline t could be calculated using the following equation:

$$PV\_new_t^G = \frac{AV_t^G}{(1 + d_t^G)^{y\_new_t^G}} \qquad \text{(Eq. 5-9)}$$

Now, the difference between the present value of the investment of network component pipeline t before and after having unit size CHP installed at node k could be calculated:

$$\Delta PV_t^G = PV\_new_t^G - PV_t^G \qquad \text{(Eq. 5-10)}$$

If the value of ΔPV_t^G is positive, it indicates that the installing CHP increases gas flow than it is without installing CHP, the future reinforcement horizon has been advanced. If the value of ΔPV_t^G is negative, it means that installing CHP benefits this line by reducing its current gas flow, deferring the future reinforcement horizon and essentially reduce the cost for future line investment that is passed to network users to pay in terms of network charges.

Taking AF into consideration and using the similar formulation of LRIC of the electricity network, LRIC of the natural gas network $LRIC_x^G$ of a unit size CHP G_{CHP} located at coupling point x could be expressed as:

$$LRIC_x^G = \frac{\left(\sum_{t=1}^{T} \frac{\Delta PV_t^G}{AF_t^G}\right)}{G_{CHP}} \qquad \text{(Eq. 5-11)}$$

The total LRIC of CHP at x in Equation 5-2 is there for the summation of Equation 5-3 and 5-11. This LRIC index matrix describes the presumptive impact of CHP at each coupling point of both the electricity network and natural gas network in terms of future reinforcement investment and network charges. Therefore, it could be used as an indicator to determine the optimal location of CHP to be installed in planning strategy with showing an economic feasibility for both network operators and network users in an multi-carrier energy system.

5.3.3. Total IC of the Multi-Carrier Energy System

As for the sizing part, the optimal capacities of CHPs to be installed in a multi-carrier energy system will be determined by minimising the total IC of both electricity network and natural gas network, the total IC indicates the future network reinforcement investment, which is partially passed to the network users to be paid in form of UoS charges.

The objective function of determining the optimal size of CHP in multi-carrier energy system is expressed by:

$$\min IC(G_n^{CHP}) = \min(\sum_{n=1}^{N} \frac{\Delta PV_n^E(G_n^{CHP})}{AF_n^E} + \sum_{t=1}^{T} \frac{\Delta PV_t^G(G_n^{CHP})}{AF_t^G}) \qquad \text{(Eq. 5-12)}$$

Where G_n^{CHP} is the gas input of CHP n.

With CHP installation, it will in general cause opposite effect to electricity network and natural gas network. In a gas network, gas-fuelled CHP system might increase the local demand and partly increase the gas flow in some pipeline. In an electricity network, as CHP playing as alternative and local supply for the demand, it might reduce power flow in some lines. The change of power flow and gas flow, not only could reflect the change of network utilisation, but more importantly as the key factor to change future reinforcement horizon, make a difference in the future InC for network operators. Therefore, appropriate siting and sizing for CHP would capture and optimise such economic benefits in long-term in a multi-carrier energy system.

5.4. Electricity and Gas Network Modelling

5.4.1. Electricity Network Modelling

Electricity network modelling in this chapter is the same as the model proposed in Chapter 4.5, which is consisted of three main aspects: power flow formulation, bus power balance and network constraints.

5.4.2. Natural Gas Network Modelling

1) Gas Flow Formulation

The gas flow formulation is based on the content in [182] which describes various types of gas flow formulation in terms of flow level, network level and pipeline characteristics. In distribution level natural gas network consists of S noes and T pipelines, the gas flow along a pipeline t between upstream node k and downstream node l, without considering elevation difference between nodes, could be ideally formulated using Weymouth equation presented as follows:

$$q_t = q_{kl} = 3.7435 \times 10^{-3} E_t \left(\frac{T_{b\_t}}{P_{b\_t}}\right)\left(\frac{P_k^2 - P_l^2}{G_t T_{f\_t} L_t Z_t}\right)^{0.5} D_t^{\ 2.667} \quad \forall\, k, l = 1, \cdots, S \quad \text{(Eq. 5-13)}$$

Where T_b and P_b are the base temperature and pressure of gas flow taking the value of 15℃ and $101kPa$, respectively, T_{f_t} is the average temperature of the gas flow which is generally 20℃, The pipeline efficiency is denoted as E, for distribution pipeline, the conventional value of it is 0.92, P_k and P_l are the upstream node pressure and downstream node pressure, Z is the gas compressibility factor typically take a value of 0.9 and G is the gas gravity of 0.6, L is the length of the pipeline and D refers to the inner diameter of the pipeline.

2) Nodal Gas Flow Balance

The total gas flow into or out of a node is the total flow from all pipelines that connect to the node. This is calculated as:

$$q_k^{Flow} = \sum_{l=1}^{S, l \neq k} \left\{ 3.7435 \times 10^{-3} E_t \left(\frac{T_{b\_t}}{P_{b\_t}}\right)\left(\frac{seg(k,l)\left(P_k^2 - P_l^2\right)}{G_t T_{f\_t} L_t Z_t}\right)^{0.5} D_t^{\ 2.667} \right\} \quad \forall\, k, l = 1, \cdots, S \quad \text{(Eq. 5-14)}$$

Where q_k^{Flow} is the total entering and leaving gas flows from an adjacent pipeline that have a connection to node k. $seg(k,l)$ is a divider to identify other nodes connection to node k, $seg(k,l)$ is 1 indicates that node k is upstream, $seg(k,l)$ is -1 indicates that node k is downstream and $seg(k,l)$ is 0 means node l have no pipeline between node k.

At each node, the gas balance is kept to assure that the total gas flow entering and injected into the node is equal to the flow leaving and ejected out of the node. This nodal gas flow balance must be met in the gas infrastructure and it is represented by:

$$\Delta q_k = q_k^{In} - q_k^{Load} - q_k^{Flow} = 0 \quad \forall\, k = 1, \cdots, S \qquad \text{(Eq. 5-15)}$$

Where q_k^{In} is the gas flow injection, q_k^{Load} is the local node load.

Similar to the electricity network formulation, a reference node in the gas network is required to be specified with a given pressure. The rest of the node pressure and the gas flow on each pipeline therefore, could be obtained accordingly.

3) Network Constraints

For the practical distributional natural gas system, constraints and limitation would be applied to the flow and flow balance formulation.

Traditionally, a pressure upper and lower limit of the pipeline could be expressed as:

$$q_{t\_min} \le q_t \le q_{t\_max} \quad \forall\, t = 1,\cdots,T \tag{Eq. 5-16}$$

Where q_{t_min} and q_{t_max} are the minimum and maximum pressure allowed in pipeline t.

5.5. Modelling of CHP and Compressor Station

5.5.1. CHP Modelling

As CHP in a multi-carrier energy system is acting as the enabler to couple the electricity network and the natural gas network. These coupling points have both electricity and gas load, the energy conversion between different vectors should be specified using a CHP static model. The role of CHP to interconnect electricity network and gas network could be seen in Figure 6-2. A gas-powered CHP system could either supply the local load or sell surplus electricity back to the grid. It consumes gas as energy input and could also be considered as local gas demand.

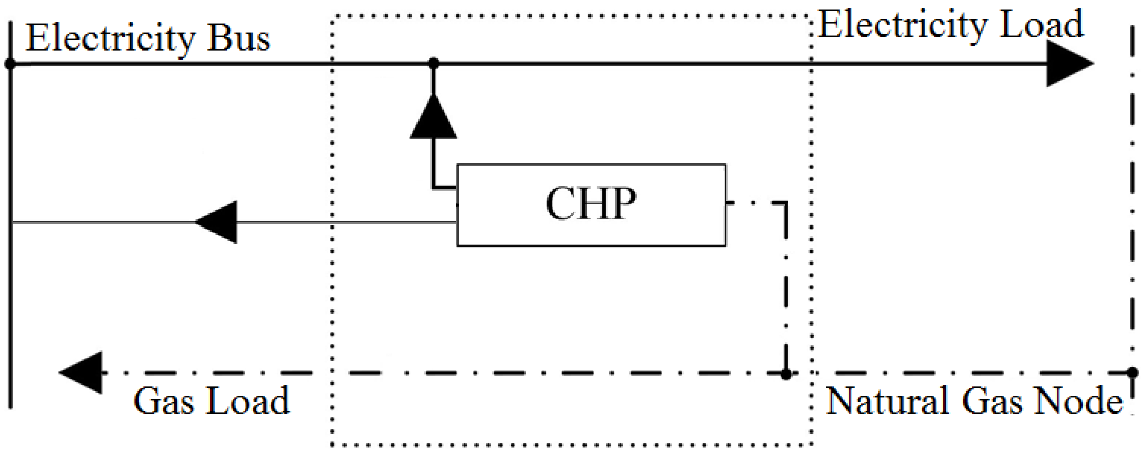

Figure 5-2. CHP to Couple Electricity Network and Natural Gas Network

In general, a gas-fuelled CHP system to generator both electricity and heating could be expressed by the following model:

$$\begin{cases} E_{CHP} = \eta_E G_{CHP} \\ H_{CHP} = \eta_H G_{CHP} \\ HtER = \dfrac{\eta_H}{\eta_E} \end{cases} \tag{Eq. 5-17}$$

Where η_E and η_H are the respective electricity and heating efficiency of the CHP. E_{CHP}, H_{CHP} and G_{CHP} are the electricity output, heating output and gas input of the system and $HtER$ refers to the heating to electricity ratio.

Using a gas-fuelled CHP system indicates that such an installation in a multi-carrier energy system would have an impact on the energy flows in both electricity and natural gas network. On one hand, electricity generation on local site would cut down the dependency from the grid and consequently reduce power flows of adjacent lines. On the other hand, local gas demand may increase and affect gas flow as well. Eventually, implementation of CHP will result in a change of network reinforcement and future investment.

5.5.2. Compressor Station Modelling

The strategy of gas network reinforcement is different from that of the electricity network. In general, for electricity network, when reinforcement horizon is due, parallel, same spec line is added to share the flow burden of the old fully utilised line. The AV of the transmission line is obtainable from the specification of the old lines. However, in the natural gas network, when reinforcement horizon is due, it requires a compressor station to be added in the line to assure enough pressure to deliver more gas. The AV of a compressor station is unknown as no past compressor station is used. Nevertheless, it could be calculated using the following steps:

Along pipeline t, the maximum gas flow could be obtained with the inlet pressure at upper pressure limit and outlet pressure at lower pressure limit, expressed as:

$$q_{t\_max} = 3.7435 \times 10^{-3} E_t \left(\frac{T_b}{P_b}\right) \left(\frac{P_{t\_max}^2 - P_{t\_min}^2}{G_t T_{f\_t} L_t Z_t}\right)^{0.5} {D_t}^{2.667} \quad \forall\, t = 1, \cdots, T \qquad \text{(Eq. 5-18)}$$

Assuming isothermal compression is applied to the work in a conventional distribution level compressor. For a compressor on the pipeline on pipeline t between nodes k and l, the energy required to compressor unit gas would be calculated by:

$$W_{i\_t} = \frac{286.76}{G_t} T_{f\_t} \log_e \left(\frac{P_{d\_t}}{P_{s\_t}}\right) \quad \forall\, t = 1, \cdots, T \qquad \text{(Eq. 5-19)}$$

Where W_i is the isothermal work done with a unit of J/kg, P_{s_t} and P_{d_t} are the suction and discharge pressure of the compressor station, respectively, to maximise the function and take advantage of the pipeline, discharge pressure could reach the upper limit of the pipe pressure P_{t_max} and the suction pressure is assumed at the lower limit of the pipeline pressure P_{t_min}.

The capacity of a compressor station could be obtained with Equation 5-20.

$$C_{G\_t} = \frac{W_{i\_t} \times q_{t\_max}}{\eta_t} \quad \forall\, t = 1, \cdots, T \tag{Eq. 5-20}$$

Where C_{G_t} is the compressor capacity in J/d, η_t refers to the compressor efficiency. Convert this value into W/s and applies the general capital cost of distribution level natural gas compressor station to obtain the final AV of a compressor station, which is represented by the following equation:

$$AV_{G\_t} = \left[\frac{C_{G\_t}/(24 * 3600)}{10^6}\right] \times 1341.02 \times 1520 \tag{Eq. 5-21}$$

Where two constant number 1341.02 and 1520 represent the power unit conversion from MW to HP and the capital cost of a conventional compressor station in £/HP [182].

5.6. Case Study

The performance of the proposed method is illustrated on a integrated electricity and natural gas distribution network shown in Figure 5-3.

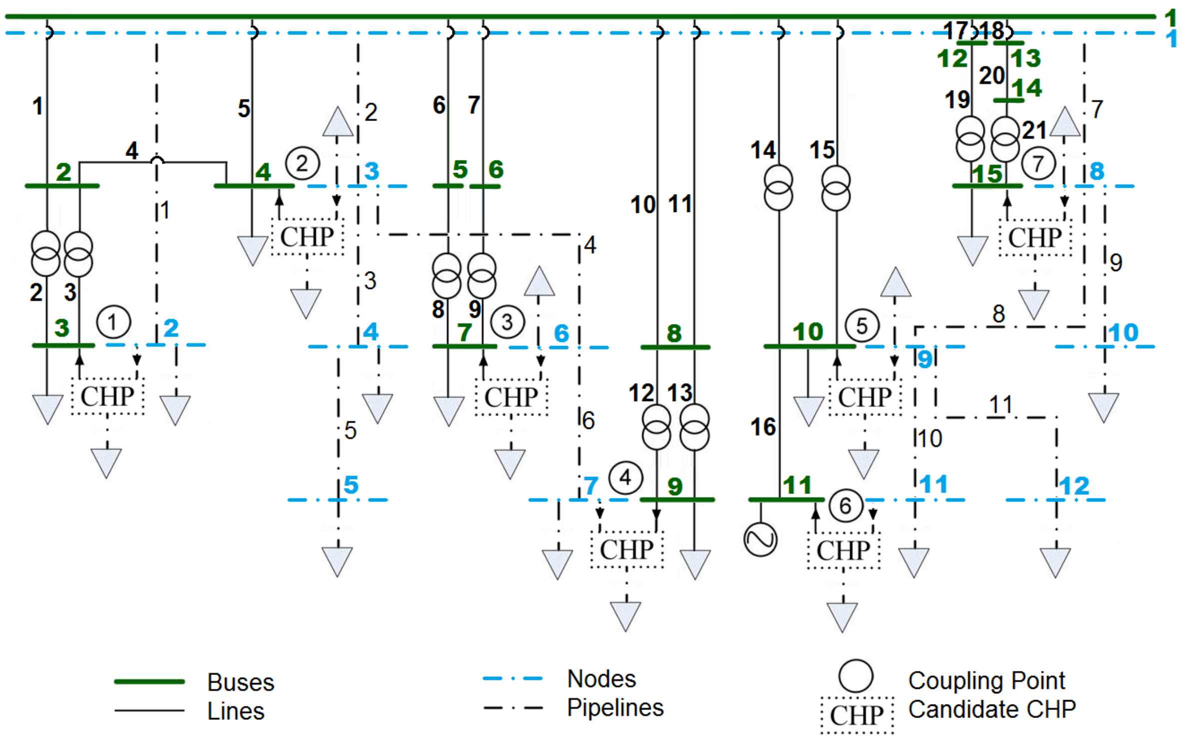

Figure 5-3. Schematic of an Integrated Electricity and Natural Gas Network

The available points to couple electricity and natural gas network by installing CHP system are shown. This multi-carrier energy system contains a 15 buses, 21 lines, 6 loads electricity network and a 12 nodes, 11 branches 11 loads. Detailed network data is shown in Appendix A-

6. Considering the spatial feasibility of the network must be geographical identical for both electricity demand and gas demand, a totally 7 potential coupling candidates for CHP installation are marked out in dot lines accordingly. Similar to the assumption made in previous chapter case studies, a load growth rate of 1.6% and a discount rate of 6.9% are taken for both energy systems to carry out the study. According to the conventional distribution level CHP employed in the UK market, a HtER ratio of 2 and an overall efficiency of 72% is taken in for CHP specification in this study [76].

5.6.1. Single CHP Planning

In this scenario, single CHP optimal planning to obtain the lowest total IC for both electricity network and the natural gas network is performed in the network shown in Figure 5-3.

1) Optimal Site

Table 5-1 partially shows the LRIC value on some important lines and pipelines of every coupling point between two energy vectors. The unit size CHP have an electricity output of 1MW, heating output of 2MW and a gas input of 4.17MW, which is equivalent to 0.10417 m^3/s.

Table 5-1. LRIC matrix for CHP in Integrated Electricity and Gas Network

Coupling Point	①	②	③	④	⑤	⑥	⑦
Electricity Network LRIC (£/MW)							
Bus / Line	3	4	7	9	10	11	15
1	-1,690	1,768	-7	-7	-7	-7	-7
2	-146	0	-1	-1	-1	-1	-1
3	-136	3	1	1	1	1	1
4	0	0	0	-234	0	0	0
10	1	1	1	-237	1	1	1
11	-1,981	-5,637	-8	-8	-8	-8	-8
12	-3	-3	-3	-275	-3	-3	-3
13	-2	-2	-2	-273	-2	-2	-2
14	2	2	2	2	-300	-292	2
15	2	2	2	2	-224	-217	2
18	28	28	28	28	28	28	-2,766
$LRIC_E$	-3,936	-3,893	14	-1,002	-514	-499	-2,881
Natural Gas Network LRIC (£/0.10417 m^3/s)							
Node / Pipeline	2	3	6	7	9	11	8
1	12	0	0	0	0	0	0

2	0	208	208	208	0	0	0
4	0	0	239	239	0	0	0
6	0	0	0	28	0	0	0
7	0	0	0	0	175	175	175
8	0	0	0	0	75	78	0
$LRIC_G$	12	208	447	475	260	263	175
Total LRIC (£/unit)							
$LRIC$	-3,924	-3,685	461	-527	-254	-236	-2,706

From Table 5-1, it could be known that among all coupling candidate points, location ① that interconnect bus 3 and node 2 have the lowest LRIC value of -3,924 £/unit, indicating that it is therefore selected as the primary location for single CHP optimal planning. Majority of this LRIC value is from electricity network with a value of -3,936 £/unit and only a few from the natural gas network with a value of 12 £/unit.

In electricity network, this assumptive unit-sized injection from the CHP system will mainly cause a £1,690 reduction of LRIC on line 1 and a £1,981 reduction of LRIC on line 11, a small portion of it comes from line 2, 3 and 18 with an LRIC value of -146, -136 and 28 £/unit, respectively. As for the natural gas network, it causes a very little increase of LRIC on pipeline 1 of £12/unit. As this coupling point candidate has the lowest total LRIC of both networks among all coupling point candidates, it is therefore selected for the site of single CHP optimal planning.

2) Optimal Size

According to this first stage, the location of installing single CHP is confirmed to be at coupling point ① which between bus 3 and node 2. The optimal size of CHP will be determined by minimising the total IC of both energy networks. The importance of IC has been emphasised in the previous chapter as it could help network operators to reduce the future network investment and therefore reduce as a cost that is passed to the network users to pay in form of UoS charge. In practical, distribution level CHP usually has a maximum electricity output of 25 MW for local network security reasons. The results in terms of site, size of CHP, network utilisation change (UC), reinforcement horizon deferral (RHD) of the single CHP optimisation is shown in Table 5-2.

Table 5-2. Single CHP Optimal Sizing with Objectives

Coupling Location	① (Between Bus 3 and Node 2)

Electricity Capacity (MW)		16 MW		Total Input (MW)		67 MW	
Objective (Total IC [£k])				-30.6			
Electricity Network				Natural Gas Network			
Lines	UC (%)	RHD (year)	IC (£k)	Pipelines	UC (%)	RHD (year)	IC (£k)
1	-25.2	30.7	-15.0	1	47	-87.7	3.85
2	-25.3	52.3	-1.0				
3	-24.9	52.2	-0.9				
5	-22.3	299	-0.04				
11	-25.4	31.7	-17.5				
IC_E			-34.4	IC_G			3.85

In Table 6-2, the results of optimal single CHP sizing in this integrated electricity and natural gas network is 16MW of electricity output with a total capacity of 67 MW, achieving to minimise the total IC of -£30.6k, which consist of -£34.4k of the electricity network and £3.84k of the natural gas network. The primary change of power and gas flow, future reinforcement horizon deferral and IC of some of the electricity transmission lines and gas pipelines are also listed in the table. In the electricity network, there are significant changes particularly in line 1, 2, 3, 5 and 11. Their utilisation is reduced by an average of 25%. The horizon deferrals of their future reinforcement are 31, 52, 52,299 and 32 years respectively. The key change would be the IC of a reduction of 15, 1, 1, 0.04 and 17.5 £k. It could be realised that majority of the reduced IC in electricity network comes from line 1 and line 11. On the other hand, a slight increased LRIC value is shown on pipeline 1 with a value of £3.85k, which is results from the gas flow utilisation of the pipeline and advancing future reinforcement horizon. The total IC reduction will be the summation of both electricity network and gas network, which is £30.6k, with the optimal size of 67 MW with an16 MW electricity output for the single CHP located at coupling point ①.

By ascending the electricity capacity of CHP at coupling point ① from 1MW to 25MW, the curves of the LRIC value of both electricity network and the natural gas network could be observed, which are shown in Figure 5-4 and some of the important changes are recorded in Table 5-3.

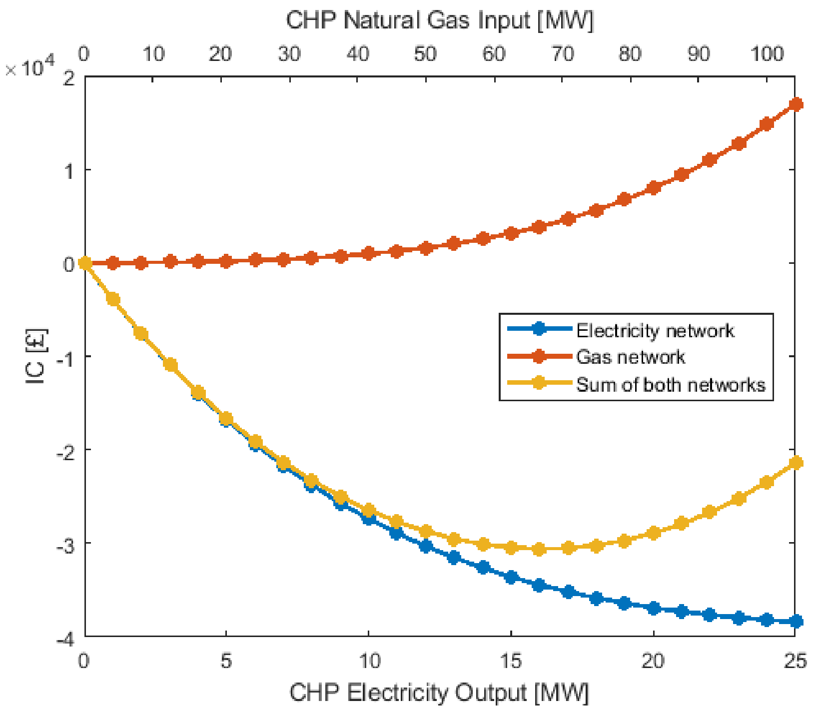

Figure 5-4. IC with Increasing CHP Capacity at Coupling Point ①.

In Figure 5-4, on one hand, the IC of the electricity network is decreasing with the growing CHP capacity. On the other hand, that of gas network increases due to the installation of CHP will increase the local gas demand and results in a gas flow increase in relative pipelines. The total IC of both networks reaches the minimum when CHP is sized at 16 MW electricity output and a total input of 67MW.

Table 5-3. Future Investment Cost Change for CHP at Chosen Site

	Electricity Network		Natural Gas Network		
Without CHP	Average Reinforcement Horizon (year)	94.8	Average Reinforcement Horizon (year)	88.4	
With CHP Size	RHD (year)	IC (k£)	RHD (year)	IC (k£)	Total IC (k£)
1	-0.6	-3.9	1.0	0.01	-3.9
5	-3.1	-16.8	3.8	0.17	-16.6
10	-7.2	-25.7	6.1	0.95	-24.8
15	-15.2	-33.6	7.7	3.1	-30.4
16	-22.2	-34.4	8.0	3.9	-30.5
20	-15.6	-36.9	9.0	8.0	-28.9
25	-20.2	-38.4	10.0	17.0	-21.4

The original multi-carrier energy system without CHP installation has average reinforcement horizon of 94.8 years of the electricity network and 88.4 years of the natural gas network when taking load growth into consideration. By increasing CHP electricity capacity from 0 MW to practical limitation of 25MW, it is obvious that electricity network reinforcement horizon and IC drop tremendously and reach the minimum at 16 MW. As for the natural gas system, it is vice versa. Future reinforcement horizon is advancing and IC is increasing slowly at the low CHP capacity then grow significantly when CHP size is becoming greater. Situations of two network are totally opposite due to the different energy flow change. CHP supplies local electricity demand therefore reduce power flow required from the grid but it also increases the local gas load as fuel to be burned. Considering the different impact of CHP for two energy network, an optimal solution to obtain minimum IC is found at CHP with an electricity output of 16 MW and a total capacity of 67 MW.

5.6.2. Multiple CHPs Planning

In this scenario, three CHPs are required to be installed to optimally plan the same multi-carrier energy system from the IC point of view.

1) Optimal Sites

Based on the LRIC matrix index results in Table 5-1, the optimal sites for three CHP to be installed in the network with the lowest LRIC value. They are coupling point ①, ② and ⑦ with a respective LRIC value of -3,924, -3,685 and -2,706 £/unit. The advantages of the first location have been analysed in the previous case study.

The second location to be selected between bus 4 and node 3 for multiple CHP planning, has an electricity network LRIC of -3,893 £/unit and a natural gas network LRIC of 208 £/unit. For the electricity part, though such assumptive unit size CHP would increase LRIC of line 1 by 1,768 £/unit, it will significantly reduce that of line 11 by 5,637 £/unit. For the natural gas part, such measure would slightly increase LRIC of pipeline 2 by 208 £/unit.

The third location at coupling point ⑦ is between bus 15 and node 8 with an electricity network LRIC of -2,881 £/unit and a natural gas network LRIC of 175 £/unit. The majority of electricity network LRIC is contributed by the LRIC reduction from line 18 with a value of 2,766 £/unit. Natural gas network LRIC is mainly from pipeline 7.

These three candidates have lowest LRIC value in ascending order, thus they are selected at the optimal site for the multiple CHPs planning.

2) Optimal Sizes

The results of optimal sizes of CHPs, and its impact on the majority of the network components, in terms of network UC, RHD and IC reduction are shown in Table 5-4.

Table 5-4. Multiple CHP Optimal Sizing with Objectives

		First CHP		Second CHP		Third CHP	
Optimal Site		① (Bus 3/Node 2)		② (Bus 4/Node 3)		⑦ (Bus 15/Node 8)	
Optimal Size (E/G) [MW]		13/54		9/38		10/42	
Electricity Capacity (MW)		16 MW		Total Input (MW)		67 MW	
Objective (Total IC)		-£45.2k					
Electricity Network				Natural Gas Network			
Lines	UC (%)	RHD (year)	IC (k£)	Pipelines	UC (%)	RHD (year)	IC (k£)
1	-35.3	49.0	-16.5	1	38.2	-78.2	2.03
2	-20.6	38.7	-9.6	2	10.6	-14.2	2.78
3	-20.3	38.6	-9.1	7	21.3	-27.5	3.84
5	-9.1	32.5	-0.04				
6	-15.4	66.4	-0.07				
11	-28.2	36.3	-18.1				
17	-15.9	76.0	-0.24				
18	-23.5	30.3	-16.9				
19	-15.9	101	-0.03				
21	-15.3	129	-0.02				
All lines	Average UC	Average RHD	Total IC	All pipelines	Average UC	Average RHD	Total IC
	-9.5	29.8	-53.9		6.4	15.8	8.64

The real capacities for these three CHPs from the interior point solver used in the MATLAB are 54.17, 37.5 and 41.67 MW respectively. These sizes are not applicable therefore integer is taken in the table. With electricity output of 13, 9 and 10 MW and a total capacity of 54, 38 and 42 MW, the objective, total IC of both energy networks is -£45,224, which is consisted of -£53,986 from the electricity network and £8,643 from the natural gas network.

Three CHPs employed with optimal sites and sizes has brought a great change in the electricity network. The direct influence would be the power flow change along transportation lines. It could be observed that a huge utilisation reduction is upon line 1 between bus 1 and bus 2 and line 11 between bus 1 and bus 8 with a respective value of -35.3% and -28.2%. There is also some significant line power utilisation drop on line 2, 3, 18 of around 20%. The secondary utilisation reduction of around 15% is found in line 6, 17, 19 and 21. From line future reinforcement horizon deferral point of view, the installation of multiple CHPs has caused changes of the lines to defer their future reinforcement horizon, particularly of line 1, 6, 17, 19 and 21 with deferral horizon by 49, 66, 76, 101 and 129 years. Other lines like line 2, 3, 5, 11, 18, their reinforcement horizon are deferred by around 30 years. The minimised IC of electricity network is -£53.9k, which is mainly comprised by the IC change of line 1, 2, 3, 11 and 18 with their IC of -16.5, -9.6, -9.1, -18.1 and -16.9 £k, respectively.

As for the natural gas system, the implementation of CHP has caused opposite influence compared to electricity network due to the gas consumption to fuel the CHP systems. This is mainly revealed in pipeline 1, 2 and 7. In pipeline 1, the gas flow has been increased with a utilisation growth of 38.2%, resulting in advancing in future reinforcement horizon by 78.2 years and an increase IC of £2.03k. In pipeline 2, though the pipeline utilisation is only increased by 10.6% and 14.2 years of shortening horizon of future investment to be taken, it still greatly increase the IC by £2.78k. The IC increase of pipeline 7 contributes most to the gas network IC with a value of £3.84k, results from the pipeline utilisation growth of 21.3% and advancing future reinforcement horizon of 27.5 years. The total natural gas network IC would therefore be £8,643.

Considering the IC change in both energy network, the total IC would therefore be -£45,224, which is the objective to be achieved in multiple CHP optimal sizing.

5.7. Chapter Summary

This chapter has extended the work in the previous chapter into multi-carrier energy system, which is one of the core aims to be achieved in this thesis. It proposes a novel approach for the CHP planning considering the future network investment from the network operator's perspective in an integrated electricity and natural gas system. Compared with conventional CHP planning studies, for example, using energy consumption, energy cost or environmental impact as planning criterion, this chapter managed to tackle the problem from another long-term economic point of view by reducing the future network investment, which is also partially passed to network users in forms of charges. The novelty and features of this chapter are summarised as follows:

- LRIC matrix index is used for both electricity and natural gas network as indicators to determine the optimal sites for CHP to be installed. It illustrates different network reinforcement measures for different energy vectors and services: in the electricity network, reinforcement is taken by adding parallel transportation line and in the gas network, it is done by adding compressor station to ensure gas pressure.
- Single and multiple CHP planning cases have shown the effectiveness of the proposed method and managed to minimise network future investment for operators and network charges for network users.
- The method provided in this chapter could be regarded as a practical planning tool for multi-carrier energy system owners to consider CHP long-term impact economically.
- The proposed method also addresses the potential problems for the employment of CHP as an enabler to interconnect electricity system with the natural gas system.

To sum up, by extending CHP planning in electricity network into the multi-carrier energy system, the proposed method in this chapter have become more practical and reliable in the fast developing trend of the interaction of various energy vectors and energy services.

Chapter 6.

Multi-Objective Operation of CHP in a Multi-Carrier Energy Network

THIS chapter proposes a novel method for the optimal design and operation of CHP with an EH in a local energy system with integrated energy resources. It also proposes a multi-objective function for the optimal operation.

6.1. Introduction

The concept of EH was introducted in Chapter 2. Several energy components give alternatives for small scale multi-carrier energy system planning and operation. Due to the diversity of the energy services and energy conversions, it is able to provide system control with extra reliability and robustness. It also provides flexibility for the system to operate through different energy conversions in case of certain energy shortage such as grid blackout or gas supply shortage. The work in [183] gives a general review and prospect of the smart EH in the multi-carrier energy system. In small residential sector or community sector, EH could be a critical and effective measure to provide demand response with the interaction of RE. By aggregating electricity, thermal energy, natural gas and other forms of energy, EH makes it possible for local energy users to flexibly switch the source from one to another. Optimal operation of CCHP based EH system is proposed in [184]. For regional multi-energy prosumer, a paradigm for EH that combines CHP, RE and energy storage is designed to serve the demand. Operational strategies of the EH system and dispatch of different energy vectors are optimised considering regional multi-energy prosumers. Similarly, the work in [185] optimised the operation of the EH system in order to cut carbon emission and reduce balancing costs. Case studies validated the effectiveness of the operation of the EH system and proved its ability to control energy carrier inputs within the context of EH by using a proposed hierarchical multi-agent system control structure. The work in [186] showed more theoretical approaches and illustrative examples of the EH system containing multi-carrier energies. The scheduling and controlling framework of EH is presented.

This chapter proposed a novel optimisation method to determine the operation of CHP-EH system in both long-term and short-term aspects. The objective to be achieved by the energy component operation is to minimise the total energy cost, carbon cost and InC. The EH system contains CHP, HP, PV generation and ha boiler system. MILP is used as a solver and the proposed method is implemented on a local multi-carrier energy system with real-time data to illustrate the effectiveness of the method. Based on the current demand and growth, a predictive future demand for 10 year time is used to calculate the potential future benefits from such CHP based EH system. Sensitivity analysis will also be carried out considering energy price change and carbon emission price change. Unlike some of the research using a typical network model for demonstration, this chapter is performed on real-time energy system leading to solid, convictive and practical results for the readers.

6.2. Methodology and Problem Formulation

6.2.1. Model and Solver

The general schematic of the CHP based EH system in a local multi-carrier energy network is shown in Figure 6-1.

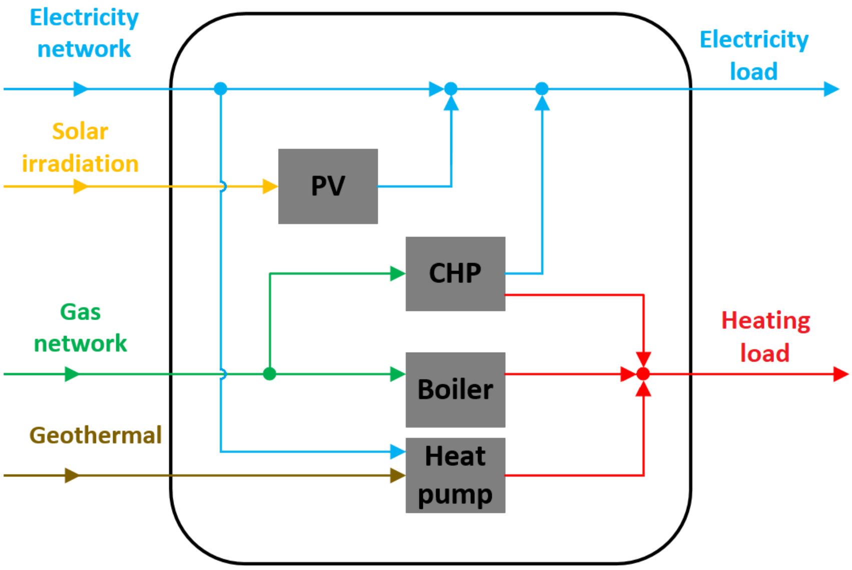

Figure 6-1. Schematic of CHP-EH in the Local Energy System

The input energy forms would be electricity, natural gas, solar irradiation to the PV penal and geothermal to the HP and the output energy vector would be electricity and heating for space and water. The main energy conversion components are PV system to convert solar power into electric power, a CHP system to burn natural gas and convert the thermal into electricity and heating, a typical boiler to convert thermal energy in the gas into heating and last but not least an HP managed to convert geothermal from the ground into heating. All energy components with limitations, different energy networks with constraints, and their interdependency between each other are modelled in MATLAB. As the objective is to minimise the relative cost, a MILP solver is used which is implemented in a toolbox called YALMIP for optimisation modelling [187]. As the load data is taken in real time every half hour for a whole year, MILP is suitable to address optimisation problem particularly for discrete variables[188].

6.2.2. Proposed Model

This subchapter presents the modelling of the proposed method including objective, energy vectors and energy conversion modelling.

1) Objective Function

A multi-objective is introduced in this study to achieve a minimum of the total InC, energy cost and the carbon emission cost of energy components of the CHP based EH system to meet local energy demand. The objective function could be represented by:

$$Min\left\{\sum_{t=1}^{T}\sum_{i=1}^{I} EC_i(t) + CC_i(t) + \sum_{s=1}^{S} InC(s)\right\} \quad \text{(Eq. 6-1)}$$

Where EC, CC and InC refers energy cost, carbon emission cost and InC respectively, t is the t^{th} time interval to a total number of T, i is the i^{th} energy vector from 1 to I in total.

The energy cost EC could be calculated using the following equation:

$$EC_i(t) = \left(G_{t,i} + P_{t,i}^{input}(s)\right) \cdot t \cdot Price_i^{Energy} \quad \forall \quad \begin{matrix} i = 1,\cdots,I \\ \mathrm{s} = 1,\cdots,S \end{matrix} \quad \text{(Eq. 6-2)}$$

Where G_i is the energy injection from input energy vector such as electricity and natural gas, P_i^{input} is the energy injection from energy vector i as input to the energy conversion component such as s gas input for CHP and boiler, solar irradiation for PV penal, $Price_i^{Energy}$ is the price of energy vector i.

The carbon emission cost CC could be calculated using the following equation:

$$CC_i(t) = \left(G_{t,i} + P_{t,i}^{output}(s)\right) \cdot t \cdot Price_i^{Carbon} \quad \forall \quad \begin{matrix} i = 1,\cdots,I \\ s = 1,\cdots,S \end{matrix} \quad \text{(Eq. 6-3)}$$

Where P_i^{output} is the energy output from the energy conversion component such as electricity and heating for CHP and boiler, electricity generation from PV penal, $Price_i^{Carbon}$ is the carbon emission price of energy vector i.

The energy price $Price_i^{Energy}$ and the carbon price $Price_i^{Carbon}$ will vary over time according to pre-agreement contract with local energy supplier and the policies published from the UK government. In the latter case studies, a price sensitivity scenario will be carried out to address the varying energy and carbon price issue. The investment cost InC of each energy component in the EH system is calculated according to the capacity, is represented by the following equation:

$$InC_s = C_s \cdot Price_s^{Capital} \quad \forall\, s = 1, \cdots, S \tag{Eq. 6-4}$$

Where C_s is the capacity of the energy component s, and $Price_s^{Capital}$ is the capital cost of energy component s.

2) Energy Node and Energy Conversion Balance

The energy flow of each energy vector i should be kept balanced, this relationship is expressed by:

$$G_{t,i} + P_{t,i}^{output} = D_{t,i} + P_{t,i}^{input} \quad \forall \begin{array}{c} i = 1, \cdots, I \\ t = 1, \cdots, T \end{array} \tag{Eq. 6-5}$$

Where $D_{t,i}$ is the energy demand for energy vector i.

For the energy conversion components in this multi-carrier energy system, the energy output should be equal to the input time its own efficiency. This is expressed by:

$$P_{t,i}^{output} = A \cdot P_{t,i}^{input} \quad \forall \begin{array}{c} i = 1, \cdots, I \\ t = 1, \cdots, T \end{array} \tag{Eq. 6-6}$$

Where A is energy conversion efficiency matrix, it is use with energy input linearly represent the output of the converter.

At each time step, the independent variables are the input of conversion devices. The energy vector input should meet the demand. The operational decision variables would thus be the output of each energy components and these variables are constrained by the limits or the capacity of the energy components. These limitations are modelled as follows:

$$\begin{cases} P_{s,min}^{capacity} \le P_s^{capacity} \le P_{s,max}^{capacity} \\ 0 \le E_s \le E_{s,max} \end{cases} \quad \forall\, s = 1, \cdots, S \tag{Eq. 6-7}$$

Where $P_{s,min}^{capacity}$ and $P_{s,max}^{capacity}$ are the maximum and minimum capacities of energy conversion component.

6.2.3. Implementation Steps

The flow chart of the proposed method in this study is shown in Figure 6-2. Detailed computational steps are described as follows:

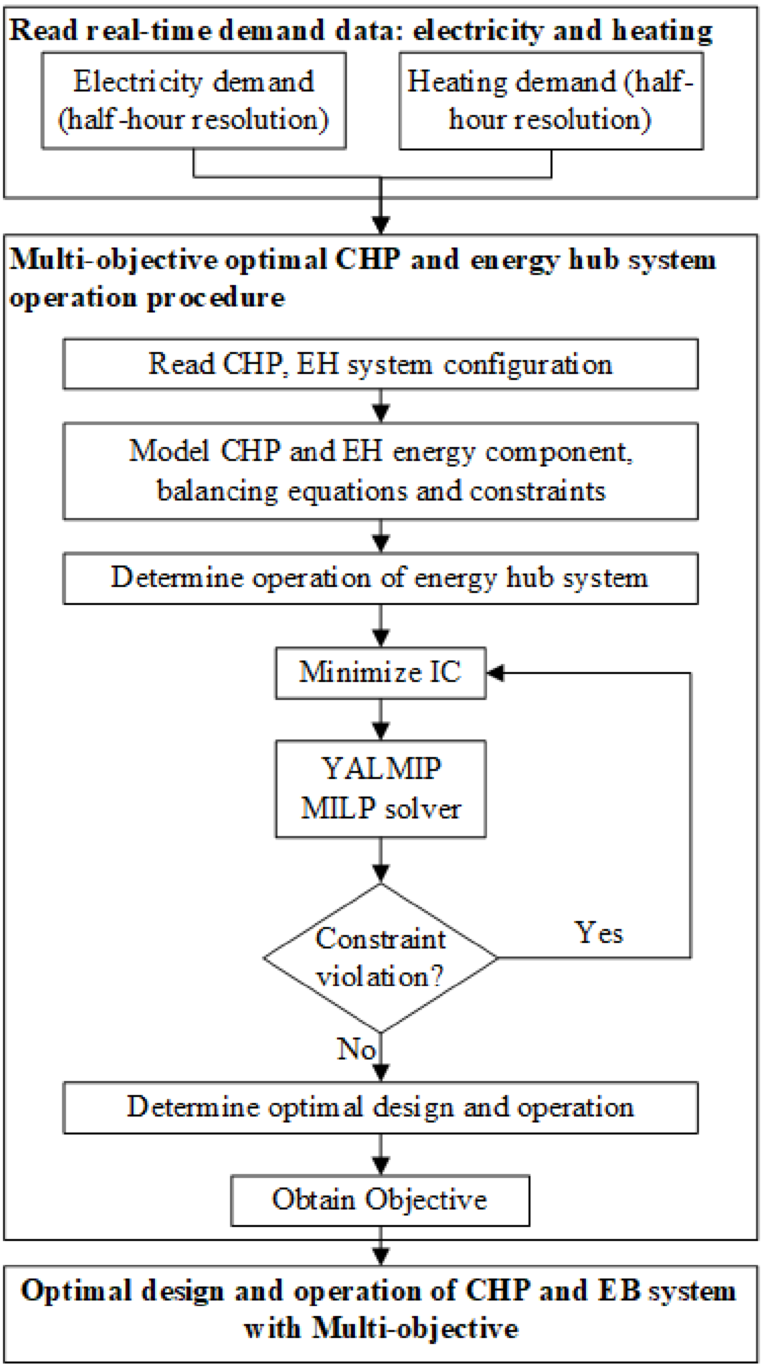

Figure 6-2. Flow Chart of Multi-Objective CHP-EH Optimisation

1) Read the input data of the local energy system including annual real-time half-hour resolution electricity demand and heating demand.

2) Read the CHP-based EH system data, this includes the efficiency, capital price, carbon price and other specifications.
3) Model the balancing equations and constraints for the optimisation of Equation 6-2 to 6-8.
4) Initialise the optimal operation of each energy component towards the objective to minimise the EC, CC and InC.
5) Using MILP as a solver and continues the progress, compare and replace local minimum toward a global solution.
6) Repeat step 4 and 5 once constraints are violated.
7) The optimisation procedure will be terminated once a global optimal is found without violation of constraints of any kind.
8) Different scenarios and sensitivity analysis will be carried on by repeat step 1 to 7.

6.3. System and Energy Carriers

6.3.1. System Data

The novel method proposed in this chapter to optimise the operation of CHP-based EH system is performed on a local multi-carrier energy system including electricity, natural gas and heating network of the University of Bath in the UK. The demand data is collected by a half-hour resolution for four whole academic years from August 2011 to July 2011. Some basic data of the system is shown in Table 6-1.

Table 6-1. Network Demand Data and Energy and Carbon Data

Energy Carrier	Price (p/kWh)	Carbon Emission (kg/kWh)	11-12 Annual Demand (BWh)
Electricity	12.894-17.085	0.412	27
Natural Gas	3.60	0.184	-
Heating	-	-	46

Use 11-12 year's electricity and heating demand as a base, a load growth rate of 1.6% is applied to this network to estimate the demand for the future 10 years. The price of energy vectors such as electricity and natural gas is collected from the local energy suppliers that have a long-term contract with the university [189]. The typical value of carbon emission of various energy vector could be obtained from the report published by Carbon Reduction Commitment [81].

6.3.2. Energy Components

The configurations and parameters of the energy conversion components of the CHP-EH system are shown in Table 6-2.

Table 6-2. Parameters and Configurations of Energy Components

Energy Equipment	Capacity	Capital Cost (£/kW)	Fixed Cost (£)	Efficiency (%)
CHP	3000 kWe	600	600000	80-87.8
Boiler	50000 kWth	440	100000	83
HP	1000 kWth	483	120000	4.0 (COP)
PV	2000 (m^2)	200 (£/m^2)	200000	18

Most of the data in Table 6-2 [189-191] including capacity and efficiency are collected from the RE and low carbon project at the University of Bath. The other data such as capital cost and fixed price are based on the commercial and industrial estimates. The efficiency curve and modelling of the CHP are from Chapter 2. The operating route of PV penal is based on the solar irradiation of the Somerset area, south west of the UK.

6.4. Case Study

The optimal operation of the EH system with CHP is performed to meet the local electricity and heating demand on half-hourly resolution through the year. Based on the energy price, carbon emission price, the operation of each energy component will alter to achieve minimum energy cost and carbon emission cost. Several case studies have been conducted to investigate the performance of the proposed optimisation solution in different aspects, from long term to short term scenario, payback horizons and sensitivity analysis considering energy and carbon price variation.

6.4.1. First Year CHP-EH Optimal Operation

In this case, the time interval is the first year after the implementation of the EH system with CHP in the multi-carrier energy system. The optimisation objective is therefore to maximise the economic benefit to be brought by this EH system compared with the cost without advanced technology in the local energy system. The objective function could be hence expressed by:

$$Max \sum_{t=1}^{T} \sum_{i=1}^{I} NC_i(t) - (EC_i(t) + CC_i(t)) \quad \forall \quad \begin{matrix} i = 1,\cdots,I \\ t = 1,\cdots,T \end{matrix} \qquad \text{(Eq. 6-9)}$$

Where NC refers to normal cost without the implementation of the CHP-EH technology, which also contains energy cost and carbon emission, it could be calculated based on the electricity and heating demand through the year. Without energy conversion brought by EH system, electricity could solely supply electric load, and heating demand are supplied by mostly gas network using existing low efficient boiler and few by DH system.

The operating curves of each energy device in 30-min resolution for the first year of electricity, heating and natural gas are shown in Figure 6-3. Figure 6-3(a) shows the energy device operation of electricity vector including load demand, CHP electricity output, HP input, PV output and electricity supply from local grid. Figure 6-3(b) shows the energy device operation of heating including heat load demand, CHP heating output, HP output and boiler output. Figure 6-3(c) shows the gas demand from the local gas network and operation curves of CHP and boiler gas input, separately.

Figure 6-3(a) shows the annual electricity vector related energy components optimal operation in 30 minutes time resolution. The electricity demand load (dark blue line) fluctuates between 1000kW to 6000kW during summer time and increases by around 1000kW during winter time from October to January. A significant drop at the end of December could be observed due to the Christmas holiday. CHP (orange line) sometimes fully operates by reaching maximum electricity output at 3000 kW and sometimes drop below that value according to the demand. HP system (yellow line) operational period is about to start on mid-September and end on May due to the increasing load at the heating demand. Most of its operation time is fully operated with an electricity input of 250kWe to produce a 1000kWth heating output.

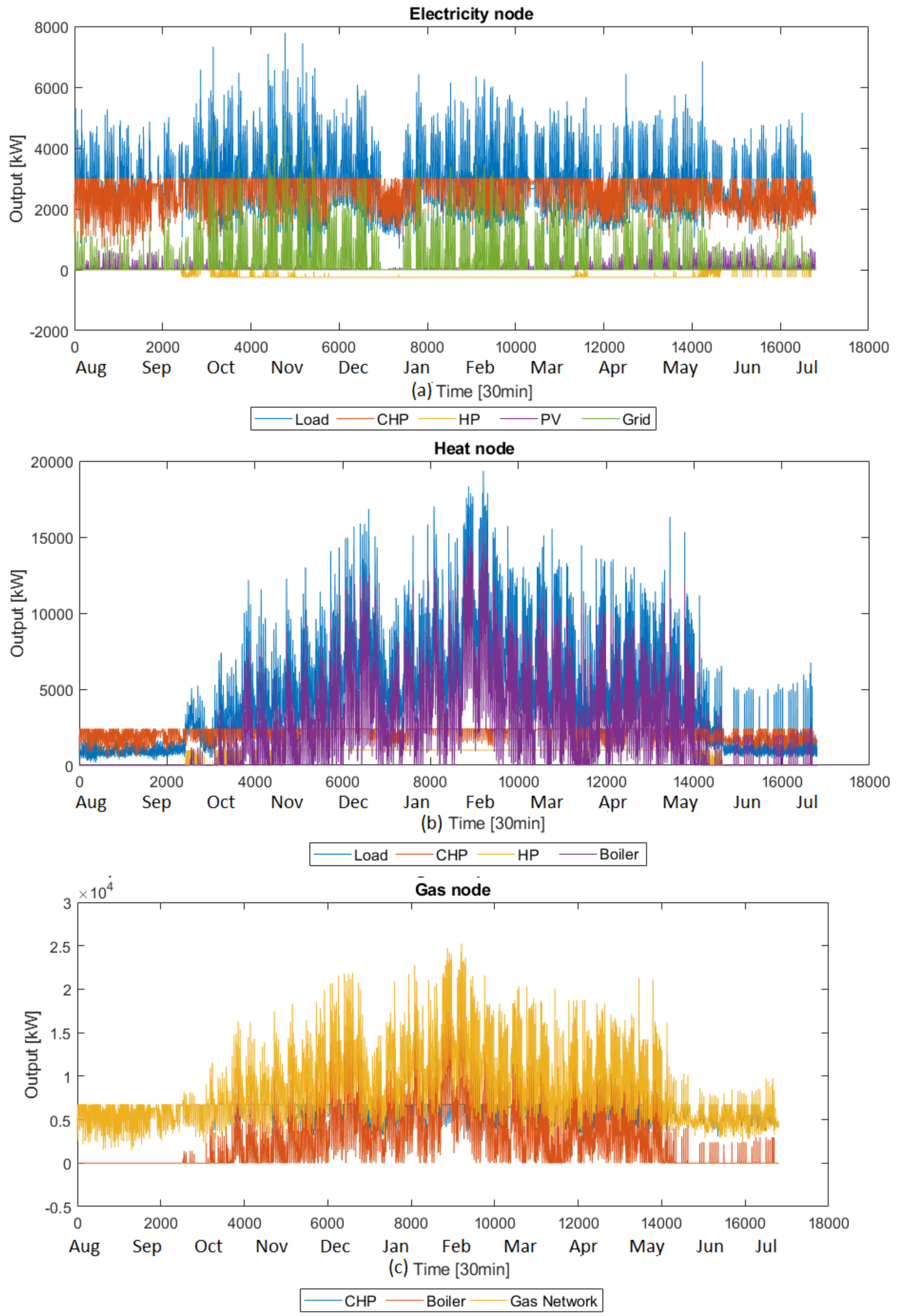

Figure 6-3. First Year Operations: (a) Electricity; (b) Heating and (c) Gas.

PV system's (purple line) optimal operation during the year is based on the solar irradiation locally. While in sunny summer days from April to September, the operational curve and electricity output of PV system could be observed clearly, in cloudy winter days from November to the end of February, the electricity output is negligible compared to the level of the electricity demand. The rest of the electricity beside energy conversion equipment is supplied by the local grid (green line). If there are no CHP-based EH system installed in this network, the whole electricity demand load will be fully supplied by the local electricity grid, where the green line should match with the dark blue line, which represents the normal operation patterns.

Figure 6-3(b) shows the annual heating load related energy components optimal operation in 30 minutes time resolution. The major difference between electricity load and heat load is their dependency on temperature. While electricity load fluctuates but keeps at the same level, heat load altered tremendously from summer to winter. In this figure, heat load (dark blue line) is kept within 2500kW from August to September and next June to July, apart from the fact that summer vacation. This load increase rapidly to 10,000 to 15,000 kW in the winter time with the highest load reaching 20,000kW. The heat output from CHP (orange line) could successfully handle the demand in hot days while the heat load level hasn't exceeded the maximum heating output of the CHP system. While in colder days from October to next May, the total output of both CHP and HP system (yellow line) could only contribute a small part of the heating demand, while the rest huge amount of it is supplied by the boiler (purple line) with greater capacity. If there is not energy technology installed in heat load, the whole heating system is mainly supplied by an existing low-efficiency boiler.

Figure 6-3(c) is the gas related energy components optimal operation patterns. The total gas load (yellow line) is comprised of the CHP gas load (dark blue line) and the boiler gas load (orange line). According to the operation of CHP and boilers in Figure 6-3(a) and (b), it is known that CHP operates through the year while boiler mostly operates in cold days to meet the increasing heat demand. This could be reflected by their respective operation patterns in the gas node.

The results of the objective in this case study are shown in Table 6-3.

Table 6-3. Objectives for the First Year

	With CHP-EH System	Original Energy System	Objective
Cost (Energy/ Carbon) (£M)	3.086 (2.946/0.140)	5.310(5.132/0.178)	2.224

Carbon Emission (CO_2) (tonnes)	13979	17866	3887

In this table, the normal cost in Equation 6-9 is £5.310M. This cost consists of two part, one is the energy cost including electricity and gas which is £5.132M and the other part is the carbon emission cost which is £0.178M. By applying the proposed method on the local energy system, with the optimal operation of each energy device, the total cost would be £3.086M which £2.946M is from energy cost and £0.140M is from carbon emission cost. Therefore the maximum saving from the optimal operation of CHP-based EH system for the first year is £2.270M with a carbon emission reduction of 3,887 tonnes from 17,866 tonnes to 13,979 tonnes. This cost saving accounts for over one third of the original energy system without CHP and EH, indicating the performance of the optimal operation is economic-effective in terms of energy cost and carbon reduction.

6.4.2. Optimal Operation for 10 Years

By applying the demand growth rate for future load estimation and using the MILP solver, the optimal operation of each energy component in the CHP EH system could be obtained in order to achieve the objectives of minimum energy cost, carbon cost and InC. The last year's energy equipment operational curves in 30 minutes resolution are shown in Figure 6-4 for electricity, heating and natural gas network.

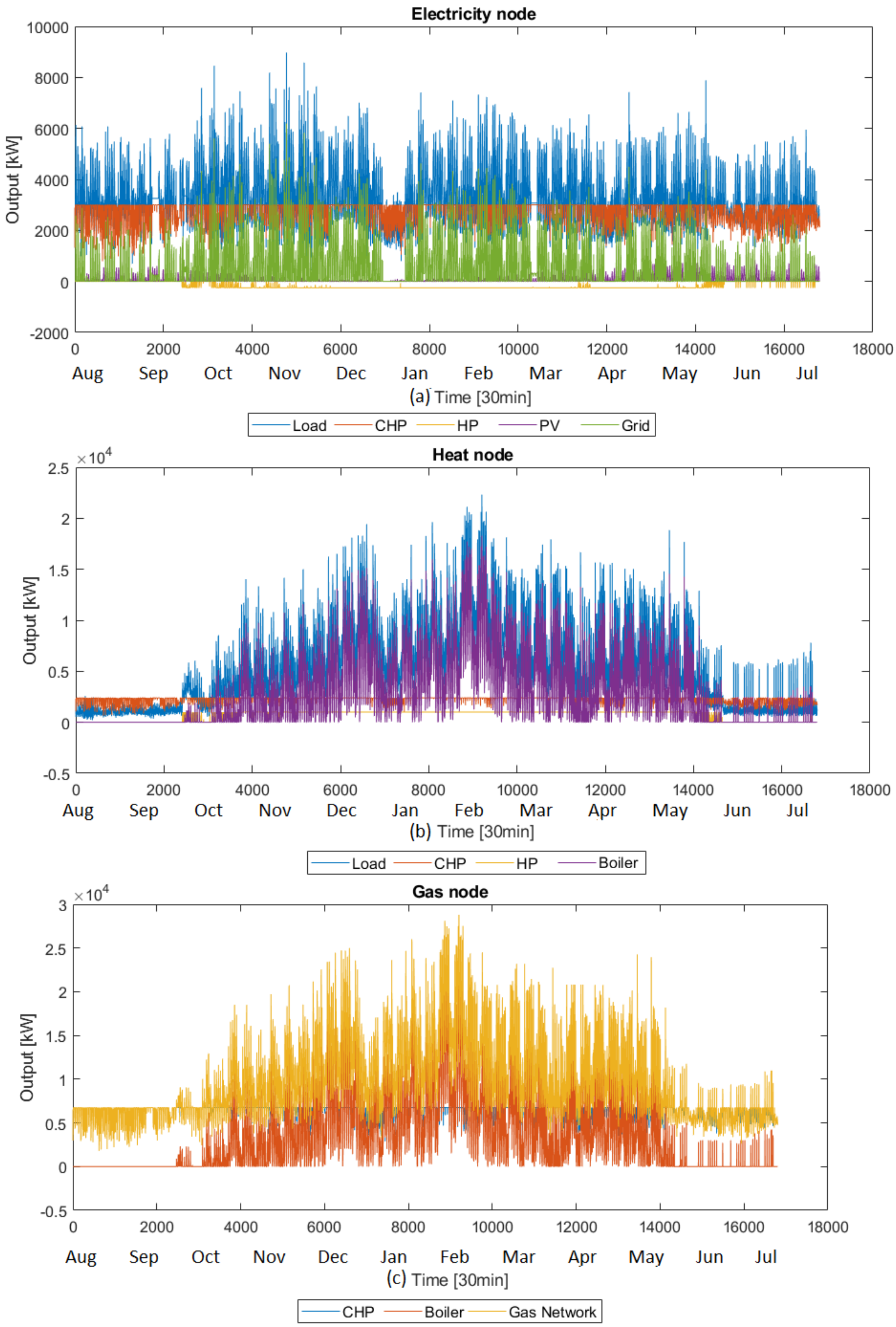

Figure 6-4. Last Year Operations: (a) Electricity; (b) Heating and (c) Gas

According to an annual demand growth rate of 1.6%, the load demand growth for the last year of 2020 to 2021 in ten year time frame would be 1.016^9 times of the first year's load demand in 2011 to 2012, which equals to about 1.15 times, this growth is observable from the dark blue curve representing new electric load in Figure 6-4(a). From Figure 6-4(a), it could be seen that CHP is still a priority supplier for local electricity demand. Its operation curve (orange line) reveals that it follows the electricity load and reach maximum capacity when the load is greater than its electricity capacity. HP system (yellow line) begins to operate when the weather starts to get cold in favour to provide heating. PV penal (purple curve) operates with the local irradiation which hasn't changed much compared with that in Figure 6-3(a). In comparison with the increasing electric load level, the influence of HP and PV to electricity node become less significant due to the capacity constraint. And the electricity supply from the grid (green line) is becoming more and more dominant with the load growth in ten years' time.

The operation of energy equipment for heating for the last year haven't changed much in Figure 6-4(b). This could be divided into two parts according to the temperature level. When the temperature is hot in summer time, CHP (orange line) and HP (yellow line) could still manage the heating demand. When the temperature gets lower and weather becomes colder, particularly from the end of October to next May, boiler (purple line) is the dominant heating generator to meet the enormous heating demand.

In the gas node, the boiler has consumed most of the gas and CHP accounts for the rest of the gas load shown in Figure 6-4(c). The operation curve of the boiler (orange line) is particularly high in colder days and CHP's gas input curve proportionate less in the total gas load than it used to be in Figure 6-3(c).

From the operation pattern of all energy conversion components, two features could be summarised: first, all energy devices have actively participated in the optimal energy service delivery to achieve the objectives; second, with the growth of the demand in both electricity network and heating network, the capacity of energy technologies has become a constraint toward optimal goal, resulting in a less significant impact to the energy network.

Table 6-4. Objective against the Normal Cost

10 years operation	EC (£M)	CC (£M)	IC (£M)	Total (£M)	Carbon Emission (k tonnes)
With CHP-EH system	32.60	1.52	13.11	47.23	152
Original Energy System	55.06	1.92	-	56.98	192

Difference	-22.46	-0.4	-	-9.75	-40

The results of the objective for a ten years frame optimal CHP-EH system operation is shown in Table 6-4. The objective of minimum energy cost, carbon cost and InC for 10 year time internal is £47.28M. This value is composed of £32.08M energy cost including electricity and natural gas, £1.52M of carbon emission cost and a total investment for energy conversion technology of £13.68M. The carbon emission during ten years' time is 152 thousand tonnes. By comparing with the results without the installation and operation of CHP based EH system, the performance of the proposed method is more convictive. If this growing demand system is supplied only by local grid for electricity and existing boiler to support heating for a 10 years' time, the total energy cost will be around £55M with a carbon emission of 192k tonnes and cost of £1.92M. Compared this with the performance of the proposed method using high efficient energy technologies, the total energy cost and carbon cost are reduced by £22.98M and £0.4M respectively, in ten years' time, not mention the fact that 40k tonnes carbon emission is reduced. Though a huge amount of money of £13.68M is required to invest at the beginning, in 10 years' time, such CHP-based EH system has recovered its InC and still make an economic saving of £9.75M.

6.4.3. Investment Payback Time

In this case study, detailed annual energy cost, carbon emission and carbon cost for 10 years' time frame have been conducted to study the investment payback period of the installation of CHP EH system in this local energy system. This data are recorded in Table 6-5.

Table 6-5. Energy Cost, Carbon Emission and Carbon Cost for Each Year

	With CHP and EH (Inc:13.68)				Without CHP and EH				Difference	
Year	EC (£M)	CC (£M)	Total (£M)	Carbon (k tons)	EC (£M)	CC (£M)	Total (£M)	Carbon (k tons)	Total (£M)	Carbon (k tons)
11-12	2.946	0.140	3.086	13.98	5.132	0.179	5.310	17.87	-2.224	-3.89
12-13	3.010	0.142	3.152	14.24	5.204	0.181	5.386	18.12	-2.234	-3.88
13-14	3.076	0.145	3.221	14.51	5.282	0.184	5.466	18.40	-2.245	-3.89
14-15	3.143	0.148	3.291	14.78	5.363	0.187	5.550	18.68	-2.259	-3.91
15-16	3.211	0.151	3.362	15.05	5.448	0.190	5.638	18.98	-2.276	-3.93
16-17	3.292	0.153	3.445	15.33	5.537	0.193	5.730	19.29	-2.285	-3.95
17-18	3.364	0.156	3.520	15.62	5.629	0.196	5.825	19.61	-2.305	-3.99
18-19	3.439	0.159	3.598	15.91	5.724	0.199	5.923	19.93	-2.325	-4.02
19-20	3.515	0.162	3.677	16.21	5.821	0.203	6.023	20.27	-2.346	-4.06

20-21	3.594	0.165	3.759	16.52	5.920	0.206	6.126	20.61	-2.367	-4.09
Change*1	-	-	21.8%	6.7%	-	-	15.4%	15.4%	-	-

*1This difference is between the first and the last year of ten years' time.

With the optimal operation of the CHP based EH system for ten years frame, costs and carbon have changed significantly. The total cost including energy cost and carbon cost for the first year under optimal energy technology optimal operation is £3.086M including £2.946M energy cost and £0.140M carbon emission cost respectively. The last year's cost during ten years frame has increased by 21.8% based on the first year's cost, with a value of £3.759M including £3.594M of energy cost and £0.165M of carbon emission cost. If the local energy system is supplied without the implementation of CHP and EH system. The total energy cost and carbon emission will start at £5.310M annually in the first year and increased by 15.4% in the last year with a value of £6.126M.

During this operation time period, the environmental benefit of carbon emission has been reduced in terms of both amount and growth rate. The carbon emission growth rate with optimal energy component operation is about 6.7% in ten years form 13.98k tonnes to 16.52k tonnes, while that of the original energy network is much higher at 15.4%, starting from 17.87k tonnes to 20.61k tonnes ten years later.

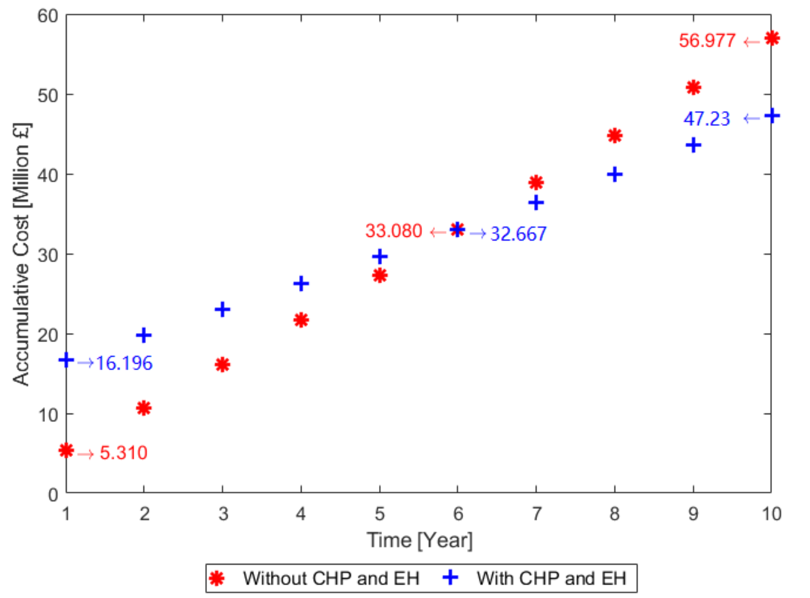

Figure 6-5. Cumulative Cost Comparison with/without CHP-EH System

The cumulative cost for the ten year interval is shown in Figure 6-5. The red star represents the cost without CHP and EH system and the blue plus mark represents the cost with optimal operation of CHP and EH system. It could be seen that in the first year, the CHP-EH cost of £16.196M, is much higher than that of the network without CHP and EH operation with a value of £5.310M. This is mainly due to the energy components InC of £13.11M, despite the factor that energy and carbon savings of the first year have already been made of £2.22M. In the next 6 years, the accumulative cost for the system without CHP and EH have increased much faster than that of the system with CHP and EH. After the sixth year, the total cost without CHP-EH system has caught up with the cost with CHP-EH system, with a total cost of £33.08M compared to that of CHP-EH system with a value of £32.667M. At this point, it is said that local energy system with optimal operation of CHP and EH have recovered their InC after 6 years and begins to make a profit from it. After ten years of modelling of the optimal operation of all energy components in the CHP-EH system, its total cost including EC, CC and IC are £47.23M. Compared with that cost without CHP and EH of £56.977M in total, the proposed method of providing optimal operation of energy conversion techniques in a local energy system managed to recover the InC within 6 years and have brought £9.747M savings with regards to energy cost and carbon emission cost.

6.4.4. Sensitivity Analysis

According to the latest announcement from 'big six' energy supply companies who share over 90% of the domestic customers in the UK, the energy price has been adjusted to increase in the next decade[192]. It is reported that the electricity price will raise by 15% and the natural gas price for the domestic customer will be increased by 4.8%. These price raise have been effective in 2017. Carbon emission price has also increased due to the goal to reduce carbon dioxide and the other GHG emission. It is reported that the carbon emission price will raise from £10/tonne in 2010 to £15/tonne in 2020 and up to £45/tonne in 2050 [193].

For this end, it is necessary to conduct a sensitivity analysis to study the increasing energy price and carbon price's impact on the optimal operation of the CHP-based EH system using the proposed method. In previous case studies, the electricity and natural gas price are 15.00p/kWh and 3.60p/kWh. According to the price change became effective in 2017, the electricity and gas price will be increased by 15% and 4.8% to 17.25p/kWh and 3.77p/kWh, respectively. By adjusting to the latest energy and carbon price, the modelling and simulation for ten years have been made for the new optimal operation of energy components, the results are shown in Table 6-6.

Table 6-6. Objective against Normal Cost with New Energy and Carbon Price

	EC (£M)	CC (£M)	IC (£M)	Total (£M)	Carbon Emission (k tonnes)
	Case in Chapter 7.4.2				
With CHP-EH system	32.60	1.52	13.11	47.23	152
Original Energy System	55.06	1.92	-	56.98	192
Difference	-22.46	-0.4	-	-9.75	-40
	Price Sensitivity Case				
With CHP-EH system	33.50	1.60	13.11	48.21	152
Original Energy System	57.79	2.02	-	59.81	192
Difference	-24.29	-0.42	-	-11.6	-40

Compare the results from the previous case and the results of energy and carbo price sensitivity analysis, two main differences could be found. First, with the growth of energy and carbon price, the total cost has increased, for the system with CHP-EH case, it is increased from £47.23M to £48.21M by 2.1%. This total cost growth is severer for non CHP-EH case from £56.98M to £59.81M by 5.0%. It reveals that the price growth would have a more profound impact economically on the system without optimal energy technology deployment. Second, by applying price change, the proposed method to optimise CHP-EH system operation could provide more cost savings of £11.6M than that of the case with constant energy and carbon price with a total saving of £9.75M. Another interesting point could be found that there is no carbon emission change in both cases. This is due to two reasons. Firstly, the latest carbon price is applied in the last year of the ten year time frame, its impact is therefore less significant. Secondly, it also reflects that the carbon emission and carbon cost is not as dominant as energy cost in the analysis. The carbon cost change due to the carbon price could be observed in the annual analysis shown in Figure 6-6.

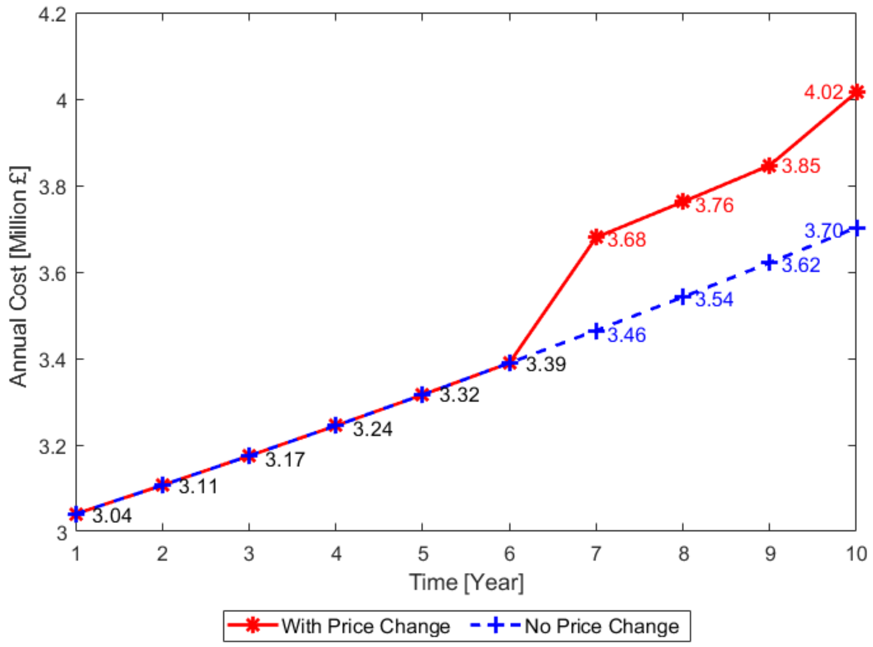

Figure 6-6. Annual Energy and Carbon Cost with/without Price Change

Figure 6-6 shows the annual energy and carbon cost with and without price change. It could be seen that for the first 6 years, the energy and carbon cost are the same as the price for both energy and carbon emission haven't changed yet. With the new energy price adjusted starting in 2017, the total cost after that year has increased significantly from £3.46M to £3.68M annually. And during the following three years, the energy cost with higher energy price has averagely increased by £0.22M per year. In the last year, another turning point could be observed from the price changing cost curve which is resulting from the new carbon price set out for the customer in 2020. This carbon price growth further increases the total energy cost for the last year to £4.02M, which is £0.32M high than that of the situation without considering the price increase.

6.5. Chapter Summary

This chapter has further discussed the optimal operation of CHP with EH system in a local multi-carrier energy system. To this end, a comprehensive study combining optimal planning and operation method of CHP for multi-carrier energy system have been proposed from the work of this chapter and the previous two chapters. The content in this chapter proposes an economic-indicated approach to determine the optimal operations of various energy conversion technologies in a multiple energy vectors system including electricity, natural gas and heating network. The objective of this optimisation problem is to minimise the total energy cost, carbon cost and InC of the energy equipment. Using 30 minute load data for a year and simulate the optimal operation of energy device by considering load growth for a 10-year time frame. The key findings of this chapter could be summarised as follows:

- Optimal operations of different energy components have significantly reduced the energy cost by increasing energy efficiency, using RE, converting different energy vector and storing surplus energy in a different form for future uses.
- The results show that in a 10-year modelling of the optimal operation of CHP-based EH system, a total savings of £9.7M could be made compared with the original energy without energy technologies. The investment could be recovered after 6 years of operations. Despite the fact of energy cost savings, the total cumulative carbon savings of about 40 thousand tonnes could be achieved.
- A sensitivity analysis is carried out to investigate the impact of energy and carbon price change to the proposed method. Results showing that though energy and carbon price would slightly increase the optimum from the operations of CHP-based EH system by considering energy cost, carbon cost and InC, the actual savings it will be higher due to the fact that such price increase will tremendously increase the total cost for the original system without CHP-EH.

To summarise, the proposed method of optimising the operation of CHP and other EH components by considering the energy cost, carbon cost and investment could give the local network owners an instructional guide of how to utilise their energy components properly.

Chapter 7.

Conclusions and Future Work

THIS chapter summarises the key findings and major contributions from this research projects, and proposes the potential future impartments and works that could be made after this thesis.

7.1. Conclusions

Nowadays, the fast development of interacting multiple energy vectors, the realisation of decarbonisation and the further infiltration of various energy conversion technologies to enable different energy services have caused some challenges to the existing planning and operation strategies in a multi-carrier energy system. CHP, as a high efficient, low carbon technology to generate both electricity and heating for local energy users, plays a critical role in the process of decarbonisation and the implement of the multi-carrier energy system. However, due to the problems brought forward by the stress on the further penetration of CHPs, increasing demand side load and the promotion of energy efficiency, the optimisation of CHP in terms of planning and operation thus need to be evolved to cope with the problems appropriately.

The prior works in the optimal planning and operation of CHP in multi-carrier energy system are expected to be able to recover InC, reduce energy cost and carbon emission for CHP owners. However, being able to provide a future cost-reflective signal to the integrated energy network is also a major drive to the planning and operation strategies, which has not been well recognised in the prior works. Thus, thus thesis has carried out intensive research on this aspect and proposed a novel method for the planning and operation of CHP in multi-carrier energy system by considering the future InC for the network operators.

Correlation Identification between Gas and Temperature

The proper planning and operation of CHP in the multi-carrier energy system are depending on the load characteristics. Thus it requires the information of the related energy loads. There have been a lot of research on the electricity load characteristic and the factors to have an impact on the load. Such analysis has been mature and fairly easy to implement to identify the factors having an influence on electricity load and could further be used to model load prediction as future load data for the optimal CHP operation. However, the gas demand characteristics and the identification of the influencing factors on it have seldom been studied. It is expected that identifying a factor to closely related to gas demand will not only be applied to the modelling of gas load characteristic and taken as a theoretical cornerstone for gas load prediction, but also applicable to the optimal planning and operation of the energy technologies that engaged to the natural gas network. To this end, a study on identifying the correlation between natural gas consumption and the temperature is conducted.

- The proposed method to identify the correlation between gas consumption and temperature uses a combination of techniques including outlier detection, data processing technique and linear regression. The outlier detection managed to identify and remove the outliers from the original gas-temperature data set by measuring M-distance, which is set as a reference to locate wrong and error data. The data processing technique of EMD managed to divide data into several IMFs with a residue. By applying linear regression, correlation coefficient on the pre-processed gas and temperature data could be calculated to explain how gas consumption is sensitive to the temperature change.
- To validate the correlation between gas consumption and temperature, different case studies are carried out including long term analysis for a whole year, short term analysis for the typical month of each season and a sensitivity study to examine their relationship between weekday/weekend and day/night. The performance of the proposed method is effective. Results show that from long term perspective, gas consumption is more correlated to temperature while in short term, this relationship is weakened. And the behaviour of customers would have an influence on such a relationship.

CHP Planning Considering Network Charges in Electricity Networks

In order to optimally plan CHP in the electricity network, objectives such as energy cost reduction, environmental impact reduction, InC recovery or sometimes a trade-off among these factors are considered. However, these objectives are fairly easy to be realised but neglect the long term impact of the CHP system to the electricity network. To investigate the long term impact of CHP in electricity network, a novel method for CHP optimisation is proposed by considering the future network investment and network charges, which could directly relates the CHP’s injection on the network to the future network component investment from the network operator’s point of view.

- As demonstrated, the future network investment will be paid by the network operators to cope with the network flow change and demand increase, the UoS charge is designed to partially pass this InC to the network users and customers. With the penetration of CHP into the network, CHP injection will have a significant influence on the power flow of the network, therefore it is crucial to investigate how CHP could have an impact on electrify network and converts this impact into a long term cost-reflective signal in the CHP planning strategy.

- To achieve this, an LRIC concept oriented objective is proposed to evaluate the economic benefits of optimally CHP planning into two stage. First part is to determine the optimal sites by using an LRIC matrix to evaluate unit-sized CHP's impact on the network. Second is to determine the optimal sizes of the CHP by minimising the total incremental cost of the network. The objective function, electricity network power flow and power balance with network constraints are modelled considering practical network constraints such as voltage limits and CHP capacity constraint.
- From the results of different case studies including single CHP planning, multiple CHPs planning and a sensitivity analyse considering changing loads, the optimal sites and sizes of CHPs in each case are determined to realise the objective. The total future investment of the network components, as well as the network charges, are minimised with global optimum from the outcomes of the study.
- Using LRIC as an indicator for CHP planning shows a forward-looking scheme of the change to be brought by CHP injection in terms of future economic impact on the network component investment and the decision making of the network charge to be paid by network users.

CHP Planning Considering Network Charges in Integrated Energy Network

In order to provide a novel optimisation for CHP in a multi-carrier energy system, an extension from last work is conducted to include both electricity network and gas network into the planning strategy. To this end, the optimal CHP planning considers the future InC for both the electricity network and natural gas network. In order to represent the future InC of the gas network, a new gas-network-featured LRIC model based on analytical approach is proposed to reflect the progress of how the gas network is to cope with gas flow change and demand growth. An overall expression of both electricity and gas network future reinforcement cost is demonstrated. The novelty and key findings of this work are described as follows:

- An LRIC matrix of the gas network is proposed due to the difference in regard to the network future investment between electricity and gas network. Gas network future reinforcement is taken by adding compression station to provide enough gas pressure for gas transportation, unlike the measures of electricity network by adding parallel transmission lines to meet the growing demand. Gas network, gas flow and power balance are formulated in this work.

- CHP as an enabler to couple electricity network with the gas network by converting thermal energy into electricity is modelled. A combined LRIC model as an objective could examine the long term impact on the network by incorporating them into simulations in terms of the respective network component utilisations, future reinforcement horizon and future network investment of electricity and gas network.
- The proposed CHP optimal planning method in multi-carrier energy system is a good supplement of the original CHP planning method in electricity network not only because of its applicability for multiple energy vectors but also because of the additional insights from the interim results. It provides further information to the readers about the network usage and potential charges.
- The case studies for single and multiple CHP planning have shown the performance of the proposed method and proven to be effective to minimise the total future investment of both electricity network and natural gas network from the operators perspective and consequently minimise the UoS charge passed from it from the network users perspective. The method proposed could, therefore, be regarded as a planning indicator for multi-carrier energy system owners to investigate CHP's impact economically in the long term.

CHP Operation with Multi-Objective in Multi-Carrier Energy System

The relationship between the operation and planning of the CHP system is becoming much closer in the implementation of the multi-carrier energy system nowadays, like two sides of a coin. The planning strategy is more focusing on the long term impact to the network itself while operation strategy is more committed to investigating short term pros and cons to be brought by the CHP system itself. Therefore, the criterion for optimal CHP planning proposed in previous work is no longer appropriate for optimal CHP operation. To achieve another goal of optimal CHP operation strategy in a multi-carrier energy system, a novel method is proposed considering a multi-objective including InC, energy cost and carbon cost. The features and major contributions are summarised as follows:

- The economic-indicated objective is presented to minimise the total InC, energy cost and carbon emission cost of a multi-carrier energy system combined with different energy conversion technologies such as CHP, HP, PV, boilers, batteries and heat tank. Therefore this CHP-based EH system contains various energy vectors such as electricity, natural gas and heating node. A simplified simulation methodology is used to represent the energy conversion, and energy balance and energy component model to reduce the computation burden of the progress.
- Based on the half-hour-resolution load data of a year and a given load growth rate, optimal operations of each energy component is simulated for 10 year time. The results of the proposed optimal energy technology operation method show that a significant reduction of energy cost and carbon cost is achieved by the application of high-efficiency low-carbon technologies. Compared with the original system without the optimal operation of CHP and EH, the total cost in a 10 year time is reduced by 17%, not mention the fact that a payback period of 6.8 years and tens of thousands tonnes of carbon savings. A sensitivity analysis considering the impact of energy price and carbon price change is carried out. Results also show the proposed method for optimal CHP-EH system operation is very well performed.
- This optimal operation strategy provides a short term cost-effective signal for the network owners to make decisions on the deployment of CHP in a multi-carrier energy system. Combined this work with the previous work, this thesis proposed a comprehensive view of the CHP penetration to the multi-carrier energy system for both energy network operators and network users in either a long term aspect or a short term aspect.

7.2. Future Work

Optimal CHP Planning and Operation using Novel Gas Load Characteristics

It is noticed that though the gas and electricity load in the CHP planning is collected from the real local energy system, the load variation in the long term analysis is usually represented by a given load growth rate. With more research carried out on the optimal CHP planning and operation, the method proposed in this thesis must be improved and increase accuracy to stay competitive among others. By adopting the electricity and natural gas characteristics to model their respective load for the future, a significant accuracy and convictive performance of the proposed method will be granted compared to that by simply applying a load growth rate.

In most research in CHP planning and operation, the test system is demonstrated in an ideal condition, for example, with a constant load demand or a fixed load change rate. However, in practice, all these parameters will change significantly. Rather than using growth rates of the load into the simulation, a CHP planning and operation scheme with forecasted load could be further carried out to find out the real performance of the proposed method and therefore increase the accuracy of the results, presenting the readers with a real, convicting outcome.

On one hand, modelling of electricity could be inspired by a vast number of studies on the electricity load characteristics. On the other hand, similar studies on gas load are limited. This also why the work is done in chapter 3 to be used as preparatory analysis to study the factors such as temperature that might have a profound impact on the gas load. Despite the temperature, attention should also be paid to special events such as holidays, heat-waves, cold snaps and other situations to have an impact on the normal pattern of the gas load. With all these factors to be considered and modelled through the choice of input variables and their transformation, gas load characteristic could be established. From both electricity and gas load characteristics, the load patterns to be used in the planning and operation strategy could be modelled.

Heat and Cooling Network Interaction in Multi-Carrier Energy System

Presently, the multi-carrier energy system only takes the electricity network and the gas network into consideration to determine the optimal sites and sizes of CHP planning. As a CHP system could generate both electricity and heating at the same time, it is critical to include its impact on the heating network. Further, CCHP requires analysis on the cooling network.

It is known that heating load could be divided into space heating and water heating. There are some difficulties to realise the formulation of the heating network at the current stage. Firstly, lack of data to form heat load. Electricity load and gas load in their respective network are measured and recorded by the meters to form their own load profile and load patterns. There is no equipment of any kind to particularly measure heating load which is widely accepted in the market currently. Secondly, as heating serving both space and water, each one of them may have their own load characteristic, hence it is difficult to generalise them into a single load. Thirdly, most of the domestic heating is supplied by the electric heaters or boilers on-site, hence the heating load is separated from each other unless the DH or DG is participated locally to connect the load into a network. Fourthly, the new concept of how reinforcement and the investment heating network is taken place should be carefully studied. The principle of how the heating network is charged to the users is also required to be figured out.

Nevertheless, by taking heating network into the consideration of optimal CHP planning will give the reader an insight of how CHP could have an economic impact on the heating network in the future and increase the feasibility of the proposed method.

Formulate UoS Charge

In terms of the UoS charge to be paid by the network users, the content introduced in this thesis is still limited. It is known that the UoS charged is paid to the energy supplier, who purchases energy from generation companies on customer's behalf and is charged by the network operators who deliver the energy to customers demand. Hence it is a charge from network users to network operators through energy suppliers. This charge is used for construction, maintenance and future reinforcement of the energy network. Though in this thesis, the formulation of network future InC for both the electricity network and gas network are clearly specified, there is no formulation on the UoS charge for the network users.

The principle, methodology for deriving future network InC to a UoS charge of different energy network is therefore required to be comprehensively reviewed. The formulation of UoS charge from the electricity network is different from that in the natural gas system. For example, electrify distribution network UoS is calculated using a combination of two charging methodology called Common Distribution Charging Methodology (CDCM) and EHV Distribution Charging Methodology (EDCM) and gas network charge is a combination of capacity charge, interconnection point capacity charge, commodity charge and other charges.

It is important to pass this future InC onto the UoS charge to present a further insight into how optimal CHP planning could have a cost-reflective impact for the network users on the long term. As for CHP owners, this cost is a critical driver of their decision on planning strategy. By delivering both future InC and UoS charge in the CHP planning, the applicability of the proposed method will be widened for either network planners or local energy users.

Improve Modelling of CHP and Other Energy Components

With the increasing volume of DGs and REs connected to the network, their impact on different energy vectors could be enormous. Due to the stochastic nature of the energy resources, such as solar power and wind power, their intermittent generation might cause difficulties in optimal planning and operation of the multi-carrier energy system. To this end, it is therefore vital to carefully model the operation and energy conversion of these energy services. In the previous chapter of proposing optimal CHP and EH system operation method, most of the modelling of the energy conversion technologies are using static formulation, which could not accurately capture the features and characteristics of each of the energy equipment. To meet a superior standard of planning and operation with a higher level of precision modelling of the network and the components within it, the static model of the energy technologies should, therefore, be modified.

The improved models to represent CHP and other components in the EH system should be able to recognise the intermittent characteristic of the renewable and reflect their influence on the network of their perspective behaviours. On the other hand, with an improved model, their energy input and output are more accurate to be projected onto the energy loads. In this context, the operation of energy components, demand for electricity, natural gas and heating network will be calculated with precision. To summarise, the reasonably modified formulation of CHP and other energy components is vital for the improvement of the proposed operation optimisation in this thesis.

Appendix

A-1 15 Bus Electricity Network Line Data

Line No.	From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)	Capacity (MW)	Asset Value (£k)
1	2	8	0.013	0.013	0	29	1001.4
2	4	8	0.03	0.071	0	32	1845.6
3	6	8	0.027	0.069	0	32	1482.9
4	6	4	0.02	0.004	0	36	0324.7
5	8	2	0.013	0.013	0	29	1006.8
6	8	10	0.033	0.09	0.008	32	1748.7
7	8	12	0.049	0.094	0.311	21	2162.5
8	12	11	0.003	0.004	0.017	32	446.9
9	14	8	0.033	0.071	0	34	598.0
10	15	8	0.033	0.071	0	34	1165.7
11	7	5	0.024	0.05	0.006	31	1178.3
12	2	1	0.045	0.085	0	23	437.6
13	2	1	0.045	0.085	0	23	437.6
14	4	3	0.042	0.787	0	32	437.6
15	4	3	0.042	0.797	0	32	437.6
16	8	7	0.031	0.58	0	25	437.6
17	8	7	0.03	0.63	0	25	437.6
18	10	9	0.018	0.8	0	32	437.6
19	11	9	0.018	0.8	0	32	437.6
20	14	13	0.026	0.796	0	40	437.6
21	15	13	0.026	0.798	0	40	437.6

A-2 15 Bus Electricity Network Bus Data

Bus No.	Active Load P (MW)	Reactive Load Q (MVar)
1	22.75	7.49
2	0	0
3	28.40	8.20
4	0	0
5	-1.162*	0
6	12.73	10.22
7	24.50	4.90
8	0	0
9	12	3.5
10	0	0
11	0	0
12	0	0
13	3.44	0.96
14	0	0
15	0	0

*: a fixed-output micro generator is located at bus 5.

A-3 LRIC Matrix for 15 Bus Network with 50% Load Increase

Bus / Line	1	2	3	4	5	6	7	9	10	11	12	13	14	15
1	-954	6,966	8	8	8	8	8	8	8	8	8	8	8	8
2	-70	-70	-8,843	10,676	-70	-16,264	-70	-70	-70	-70	-70	-70	-70	-70
3	-36	-36	-6,588	-2234	-36	6,835	-36	-36	-36	-36	-36	-36	-36	-36
4	0	0	-39	-64	0	-21	0	0	0	0	0	0	0	0
5	-913	5532	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6	0	0	0	0	0	0	0	-210	141	-419	-412	0	0	0
7	27	27	27	27	27	27	27	-5,582	8,372	6,554	5,740	27	27	27
8	0	0	0	0	0	0	0	-50	-74	9	135	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	5	-1
10	0	0	0	0	0	0	0	0	0	0	0	-1	-2	9
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	-1034	540	10	10	10	10	10	10	10	10	10	10	10	10
13	-1049	529	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
14	-2	-2	-567	10	-2	9	-2	-2	-2	-2	-2	-2	-2	-2
15	5	5	-529	17	5	16	5	5	5	5	5	5	5	5
16	0	0	0	0	-1,103	0	-1.116	0	0	0	0	0	0	0
17	-7	-7	-7	-7	-817	-7	-831	-7	-7	-7	-7	-7	-7	-7
18	0	0	0	0	0	0	0	-39	62	-76	-75	0	0	0
19	0	0	0	0	0	0	0	-25	-37	90	87	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	1	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	1
LRIC (£/MW)	-4033	13,484	-16,531	8,438	-1,983	-9,841	-2,011	-6,002	8367	6,061	5,379	-72	-65	-60

A-4 MATLAB Code: Main Code for Electricity Network CHP Planning

```
clc;
clear all;

Multi_data;   %Read network data
[Power_flow]=Multi_lfnewton_firstPF(busData,lineData); %display all results
for the first PF

tic
[x0]=Multi_x0(busData);  %Define initial point
[lb,ub]=Multi_bound(busData);    %Define lower and upper bounds
[A,b,Aeq,beq]=Multi_lcon(); %Define linear constraints
nonlcon=@Multi_nonlcon;   %Define nonlinear constraints
fun=@Multi_fun;   %Define function to minimise

options=optimset('Display','iter','LargeScale','on','GradObj','off','Hessia
n','off');
options=optimset(options, 'MaxIter',10000, 'TolCon', 1e-10);
options=optimset(options,'MaxFunEvals',100000);
%options.Algorithm='trust-region-reflective';
%options.Algorithm='sqp';
%options.Algorithm='sqp-legacy';
%options.Algorithm='active-set';
[x,fval,exitflag,output,lambda,grad,hessian]=fmincon(fun,x0,A,b,Aeq,beq,lb,
ub,...
nonlcon,options,busNum,lineData,busData);

T=toc;
exitflag
Multi_results(fval,output,T); %Display OPF results
```

A-5 MATLAB Code: Electricity Network Formulation

```
function [Total_IC]=Multi_lfnewton(busData,lineData)
%global busVm_out PG Pflow
global busVm_out PG %Pflow
global lineP_new lineP_min_bi lineP_max_bi
global sumIC
basemva= 100;  accuracy = 0.0000001; maxiter = 1000;
j=sqrt(-1); i = sqrt(-1);
lineP_min=lineData(:,7);
lineP_max=lineData(:,8);
lineP_old=abs(lineData(:,12));
lineGR=lineData(:,13);  %Growth rate
lineAV=lineData(:,14);  %Asset value
lineDR=lineData(:,15);  %Discount rate
lineLS=lineData(:,16);  %Life span
lineAF=(1-(1+lineDR).^(-lineLS))./lineDR;    %Annuity factor
linen_old=(log10(lineP_max)-log10(lineP_old))./(log10(1+lineGR));  %Old
life span
linePV_old=lineAV./((1+lineDR).^linen_old); %Old present value



lineF = lineData(:,2); lineT = lineData(:,3); lineR = lineData(:,4);
lineX = lineData(:,5); lineC = j*lineData(:,6); lineTap = lineData(:, 9);
lineNumber=length(lineData(:,1)); busNumber = length(busData(:,1));
Z = lineR + j*lineX; y= ones(lineNumber,1)./Z;        %branch admittance
for a = 1:lineNumber
if lineTap(a) <= 0
    lineTap(a) = 1; else end
Ybus=zeros(busNumber,busNumber);     % initialize Ybus to zero
               % formation of the off diagonal elements
for b=1:lineNumber;
       Ybus(lineF(b),lineT(b))=Ybus(lineF(b),lineT(b))-y(b)/lineTap(b);
       Ybus(lineT(b),lineF(b))=Ybus(lineF(b),lineT(b));
end
end
  % formation of the diagonal elements
for  c=1:busNumber
     for d=1:lineNumber
         if lineF(d)==c
         Ybus(c,c) = Ybus(c,c)+y(d)/(lineTap(d)^2) + lineC(d);
         elseif lineT(d)==c
         Ybus(c,c) = Ybus(c,c)+y(d) +lineC(d);
         else, end
     end
end
disp('Ybus is'); disp(Ybus);
clear Pgg
%  Bus Admittance Matrix calculation ends

%   Power flow solution by Newton-Raphson method
%   Revision 1 (Aug. 99) To include two or more parallel lines
SlackNum=0; %No of slack bus
PVNum=0; %No of PV bus
%busVm=0; busVa=0;
```

```
yload=0;
deltad=0;

busFlag=busData(:,2);
busVm=busData(:,3); busVa=busData(:,4);
busPD=busData(:,5); busQD=busData(:,6);
busPG=PG;   busQG=busData(:,7);
busQsh=busData(:,9);
busVm_min=busData(:,10);    busVm_max=busData(:,11);
busVa_min=busData(:,12);    busVa_max=busData(:,13);
busPG_min=busData(:,14);    busPG_max=busData(:,15);
busQG_min=busData(:,16);    busQG_max=busData(:,17);
busGs=busData(:,18);    busBs=busData(:,19);

V=busVm.*cos(busVa) + j*busVm.*sin(busVa);
P=(busPG-busPD)/basemva;
Q=(busQG-busQD+ busQsh)/basemva;
S= P + j*Q;

for e=1:busNumber
if busFlag(e) == 1, SlackNum = SlackNum+1; else, end
if busFlag(e) == 2, PVNum = PVNum+1; else, end
ngs(e) = PVNum; % ngs is a 1*busNum matrix with all elements are PVNum
nss(e) = SlackNum;  % nss is a 1*busNum matrix with all elements are
SlackNum
end

Ym=abs(Ybus); Ya = angle(Ybus);  %Ybus is used
m=2*busNumber-PVNum-2*SlackNum;
maxerror = 1; converge=1;
iter = 0;
%%%% added for parallel lines (Aug. 99)
mline=ones(lineNumber,1);
for f=1:lineNumber
      for m=f+1:lineNumber
         if((lineF(f)==lineF(m)) && (lineT(f)==lineT(m)));
            mline(m)=2;
         elseif ((lineF(f)==lineT(m)) && (lineT(f)==lineF(m)));
         mline(m)=2;
         else, end
      end
   end
%%%   end of statements for parallel lines (Aug. 99)

% Start of iterations
clear A  DC   J  DX
while maxerror >= accuracy && iter <= maxiter % Test for max. power
mismatch
for ii=1:m
for k=1:m
   A(ii,k)=0;      %Initializing Jacobian matrix
end, end
iter = iter+1;
for busNo=1:busNumber
nn=busNo-nss(busNo);
lm=busNumber+busNo-ngs(busNo)-nss(busNo)-SlackNum;
J11=0; J22=0; J33=0; J44=0;
   for ii=1:lineNumber
    if mline(ii)==1   % Added to include parallel lines (Aug. 99)
        if lineF(ii) == busNo || lineT(ii) == busNo
```

```
            if lineF(ii) == busNo ,  l = lineT(ii); end
            if lineT(ii) == busNo , l = lineF(ii); end
         J11=J11+ busVm(busNo)*busVm(l)*Ym(busNo,l)*sin(Ya(busNo,l)-
busVa(busNo) + busVa(l));
         J33=J33+ busVm(busNo)*busVm(l)*Ym(busNo,l)*cos(Ya(busNo,l)-
busVa(busNo) + busVa(l));
                if busFlag(busNo)~=1
                J22=J22+ busVm(l)*Ym(busNo,l)*cos(Ya(busNo,l)- busVa(busNo)
+ busVa(l));
                J44=J44+ busVm(l)*Ym(busNo,l)*sin(Ya(busNo,l)- busVa(busNo)
+ busVa(l));
                else, end
                if busFlag(busNo) ~= 1  && busFlag(l) ~=1
                    lk = busNumber+l-ngs(l)-nss(l)-SlackNum;
                    ll = l -nss(l);
                % off diagonalelements of J1
                    A(nn, ll) =-
busVm(busNo)*busVm(l)*Ym(busNo,l)*sin(Ya(busNo,l)- busVa(busNo) +
busVa(l));
                    if busFlag(l) == 0  % off diagonal elements of J2
                    A(nn, lk) =busVm(busNo)*Ym(busNo,l)*cos(Ya(busNo,l)-
busVa(busNo) + busVa(l));end
                    if busFlag(busNo) == 0  % off diagonal elements of J3
                    A(lm, ll) =-
busVm(busNo)*busVm(l)*Ym(busNo,l)*cos(Ya(busNo,l)- busVa(busNo)+busVa(l));
end
                    if busFlag(busNo) == 0 && busFlag(l) == 0  % off
diagonal elements of  J4
                    A(lm, lk) =-busVm(busNo)*Ym(busNo,l)*sin(Ya(busNo,l)-
busVa(busNo) + busVa(l));end
               else end
            else , end
      else, end
   end
   Pk = busVm(busNo)^2*Ym(busNo,busNo)*cos(Ya(busNo,busNo))+J33;
   Qk = -busVm(busNo)^2*Ym(busNo,busNo)*sin(Ya(busNo,busNo))-J11;
   if busFlag(busNo) == 1
       P(busNo)=Pk; Q(busNo) = Qk; end   % Swing bus P
     if busFlag(busNo) == 2
         Q(busNo)=Qk;
         if busQG_max(busNo) ~= 0
           Qgc = Q(busNo)*basemva + busQD(busNo) - busQsh(busNo);
           if iter <= 7                 % Between the 2th & 6th iterations
              if iter > 2               % the Mvar of generator buses are
                if Qgc  < busQG_min(busNo),       % tested. If not within
limits Vm(n)
                busVm(busNo) = busVm(busNo) + 0.01;     % is changed in
steps of 0.01 pu to
                elseif Qgc  > busQG_max(busNo),    % bring the generator
Mvar within
                busVm(busNo) = busVm(busNo) - 0.01;end % the specified
limits.
              else, end
           else,end
         else,end
     end
   if busFlag(busNo) ~= 1
     A(nn,nn) = J11;  %diagonal elements of J1
     DC(nn) = P(busNo)-Pk;
   end
   if busFlag(busNo) == 0
```

```
     A(nn,lm) =
2*busVm(busNo)*Ym(busNo,busNo)*cos(Ya(busNo,busNo))+J22;  %diagonal
elements of J2
     A(lm,nn)= J33;         %diagonal elements of J3
     A(lm,lm) =-2*busVm(busNo)*Ym(busNo,busNo)*sin(Ya(busNo,busNo))-
J44;  %diagonal of elements of J4
     DC(lm) = Q(busNo)-Qk;
   end
end
DX=A\DC';
for busNo=1:busNumber
  nn=busNo-nss(busNo);
  lm=busNumber+busNo-ngs(busNo)-nss(busNo)-SlackNum;
    if busFlag(busNo) ~= 1
    busVa(busNo) = busVa(busNo)+DX(nn); end
    if busFlag(busNo) == 0
    busVm(busNo)=busVm(busNo)+DX(lm); end
 end
  maxerror=max(abs(DC));
     if iter == maxiter && maxerror > accuracy
   fprintf('\nWARNING: Iterative solution did not converged after ')
   fprintf('%g', iter), fprintf(' iterations.\n\n')
   fprintf('Press Enter to terminate the iterations and print the results
\n')
   converge = 0; pause, else, end

   if converge ~= 1
   tech= ('                      ITERATIVE SOLUTION DID NOT CONVERGE');
else,
   tech=('                      Power Flow Solution by Newton-Raphson
Method');
end
V = busVm.*cos(busVa)+j*busVm.*sin(busVa);
deltad=180/pi*busVa;
i=sqrt(-1);
k=0;
for busNo = 1:busNumber
     if busFlag(busNo) == 1
     k=k+1;
     S(busNo)= P(busNo)+j*Q(busNo);
     busPG(busNo) = P(busNo)*basemva + busPD(busNo);
     busQG(busNo) = Q(busNo)*basemva + busQD(busNo) - busQsh(busNo);
     Pgg(k)=busPG(busNo);
     Qgg(k)=busQG(busNo);     %june 97
     elseif  busFlag(busNo) ==2
     k=k+1;
     S(busNo)=P(busNo)+j*Q(busNo);
     busQG(busNo) = Q(busNo)*basemva + busQD(busNo) - busQsh(busNo);
     Pgg(k)=busPG(busNo);
     Qgg(k)=busQG(busNo);  % June 1997
  end
yload(busNo) = (busPD(busNo)-
j*busQD(busNo)+j*busQsh(busNo))/(basemva*busVm(busNo)^2);
end
busData(:,3)=busVm'; busData(:,4)=deltad';
Pgt = sum(busPG);  Qgt = sum(busQG); Pdt = sum(busPD); Qdt = sum(busQD);
Qsht = sum(busQsh);
%display busout
disp(tech)
fprintf('                      Maximum Power Mismatch = %g \n', maxerror)
fprintf('                             No. of Iterations = %g \n\n', iter)
```

```
head =['    Bus  Voltage  Angle    ------Load------    ---Generation---
Injected'
       '    No.  Mag.     Degree     MW       Mvar       MW       Mvar
Mvar '
       '
'];
disp(head)
for busNo=1:busNumber
     fprintf(' %5g', busNo), fprintf(' %7.3f', busVm(busNo)),
     fprintf(' %8.3f', deltad(busNo)), fprintf(' %9.3f', busPD(busNo)),
     fprintf(' %9.3f', busQD(busNo)),  fprintf(' %9.3f', busPG(busNo)),
     fprintf(' %9.3f ', busQG(busNo)), fprintf(' %8.3f\n', busQsh(busNo))
end
    fprintf('      \n'), fprintf('    Total              ')
    fprintf(' %9.3f', Pdt), fprintf(' %9.3f', Qdt),
    fprintf(' %9.3f', Pgt), fprintf(' %9.3f', Qgt), fprintf(' %9.3f\n\n',
Qsht)

    busVm_out=busVm;
%display lineflow
SLT = 0;
Pmatrix= sparse(busNumber,busNumber);
Qmatrix= sparse(busNumber,busNumber);
fprintf('\n')
fprintf('                           Line Flow and Losses \n\n')
fprintf('     --Line--  Power at bus & line flow    --Line loss--
Transformer\n')
fprintf('     from  to    MW      Mvar     MVA       MW      Mvar
tap\n')
for busNo = 1:busNumber
busprt = 0;
   for L = 1:lineNumber;
       if busprt == 0
           Pmatrix(busNo,busNo)=P(busNo)*basemva;
           Qmatrix(busNo,busNo)=Q(busNo)*basemva;
       fprintf('   \n'), fprintf('%6g', busNo), fprintf('      %9.3f',
P(busNo)*basemva)
       fprintf('%9.3f', Q(busNo)*basemva), fprintf('%9.3f\n',
abs(S(busNo)*basemva))
       busprt = 1;
       else, end
       if lineF(L)==busNo      k = lineT(L);
       In = (V(busNo) - lineTap(L)*V(k))*y(L)/lineTap(L)^2 +
lineC(L)/lineTap(L)^2*V(busNo);
       Ik = (V(k) - V(busNo)/lineTap(L))*y(L) + lineC(L)*V(k);
       Snk = V(busNo)*conj(In)*basemva;
       Skn = V(k)*conj(Ik)*basemva;
       SL  = Snk + Skn;
       SLT = SLT + SL;
       elseif lineT(L)==busNo  k = lineF(L);
       In = (V(busNo) - V(k)/lineTap(L))*y(L) + lineC(L)*V(busNo);
       Ik = (V(k) - lineTap(L)*V(busNo))*y(L)/lineTap(L)^2 +
lineC(L)/lineTap(L)^2*V(k);
       Snk = V(busNo)*conj(In)*basemva;
       Skn = V(k)*conj(Ik)*basemva;
       SL  = Snk + Skn;
       SLT = SLT + SL;
       else, end
         if lineF(L)==busNo | lineT(L)==busNo
             Pmatrix(busNo,k)=real(Snk);
             Qmatrix(busNo,k)=imag(Snk);
```

```
           fprintf('%12g', k),
           fprintf('%9.3f', real(Snk)), fprintf('%9.3f', imag(Snk))
           fprintf('%9.3f', abs(Snk)),
           fprintf('%9.3f', real(SL)),
               if lineF(L) ==busNo & lineTap(L) ~= 1
               fprintf('%9.3f', imag(SL)), fprintf('%9.3f\n', lineTap(L))
               else, fprintf('%9.3f\n', imag(SL))
               end
           else, end
  end
end

SLT = SLT/2;
fprintf('   \n'), fprintf('    Total loss                           ')
fprintf('%9.3f', real(SLT)), fprintf('%9.3f\n', imag(SLT))
disp('P Power flow matrix is');disp(Pmatrix);
disp('Q Power flow matrix is');disp(Qmatrix);

fprintf('\n')
fprintf('      --Line--  --Branch  Power  Flow--      --IC--   --Branch
Capacity--\n')
fprintf('      from  to     MW      Mvar      MVA          £         Min
Max\n')
sumICF=0;
sumICT=0;
for busNo = 1:busNumber

    for L = 1:lineNumber;
       if lineF(L)==busNo
           k = lineT(L);
       In = (V(busNo) - lineTap(L)*V(k))*y(L)/lineTap(L)^2 +
lineC(L)/lineTap(L)^2*V(busNo);
       Ik = (V(k) - V(busNo)/lineTap(L))*y(L) + lineC(L)*V(k);
       Snk = V(busNo)*conj(In)*basemva;
       Skn = V(k)*conj(Ik)*basemva;
       SL  = Snk + Skn;
       SLT = SLT + SL;
       Pnk=abs(real(Snk));
       Qnk=abs(imag(Snk));
       lineP_new=Pnk;
       linen_new=(log10(lineP_max(L))-
log10(lineP_new))./(log10(1+lineGR(L)));
       linePV_new=lineAV(L)./((1+lineDR(L)).^linen_new);
       deltaPV=linePV_new-linePV_old(L);
       IC=deltaPV.*lineAF(L);
       sumICF=sumICF+IC;
       lineP_min_bi=lineP_min(L);
       lineP_max_bi=lineP_max(L);


       elseif lineT(L)==busNo  k = lineF(L);
       In = (V(busNo) - V(k)/lineTap(L))*y(L) + lineC(L)*V(busNo);
       Ik = (V(k) - lineTap(L)*V(busNo))*y(L)/lineTap(L)^2 +
lineC(L)/lineTap(L)^2*V(k);
       Snk = V(busNo)*conj(In)*basemva;
       Skn = V(k)*conj(Ik)*basemva;
       SL  = Snk + Skn;
       SLT = SLT + SL;
       Pnk=abs(real(Snk));
       Qnk=abs(imag(Snk));
```

```
        lineP_new=Pnk;
        linen_new=(log10(lineP_max(L))-
log10(lineP_new))./(log10(1+lineGR(L)));
        linePV_new=lineAV(L)./((1+lineDR(L)).^linen_new);
        deltaPV=linePV_new-linePV_old(L);
        IC=deltaPV.*lineAF(L);
        sumICT=sumICT+IC;
        lineP_min_bi=lineP_min(L);
        lineP_max_bi=lineP_max(L);
        else
        end
        if lineF(L)==busNo | lineT(L)==busNo
            Pmatrix(busNo,k)=real(Snk);
            Qmatrix(busNo,k)=imag(Snk);
          fprintf('%6g', busNo),
          fprintf('%6g', k),
          fprintf('%9.3f', Pnk), fprintf('%9.3f', Qnk)
          fprintf('%9.3f', abs(Snk)),fprintf('%12g', IC),
          fprintf('%9.3f', lineP_min_bi),fprintf('%9.3f\n', lineP_max_bi),
          %fprintf('%9.3f', real(SL)),
          %if lineF(L) ==busNo & lineTap(L) ~= 1
          %    fprintf('%9.3f', imag(SL)),% fprintf('%9.3f\n', lineTap(L))
          %else fprintf('%9.3f\n', imag(SL))
          %end
        else
        end
    end
end
sumIC = (sumICF+sumICT)/2;
fprintf('    \n'), fprintf('    Total IC                          ')
fprintf('%9.3f', sumIC)
fprintf('\n')


Pmatrix(logical(eye(size(Pmatrix)))) = 0;
Qmatrix(logical(eye(size(Qmatrix)))) = 0;
Pabs=abs(Pmatrix);
Qabs=abs(Qmatrix);
for fff = 1:busNumber;
for  ttt = 1:busNumber;
if Pabs(fff,ttt)>Pabs(ttt,fff)  && fff~=ttt
    Pabs(fff,ttt)=Pabs(fff,ttt);
    Pabs(ttt,fff)=0;
else Pabs(fff,ttt)=Pabs(ttt,fff); Pabs(ttt,fff)=0;
end
end
end
for fff = 1:busNumber;
for  ttt = 1:busNumber;
if Qabs(fff,ttt)>Qabs(ttt,fff)  && fff~=ttt
    Qabs(fff,ttt)=Qabs(fff,ttt);
    Qabs(ttt,fff)=0;
else Qabs(fff,ttt)=Qabs(ttt,fff); Qabs(ttt,fff)=0;
end
end
end
Pabs;
Qabs;
Pflow=Pabs(Pabs~=0);
Qflow=Qabs(Qabs~=0);
disp('P Abs power flow matrix is');disp(Pabs);
```

```
disp('P Power flow is');disp(Pflow);
disp('Q Abs power flow matrix is');disp(Qabs);
disp('Q Power flow is');disp(Qflow);
busPG_out=busPG;    busQG_out=busQG;
busP_injection=P*basemva;busQ_injection=Q*basemva;
disp('busPG_out is');disp(busPG_out);
disp('busQG_out is');disp(busQG_out);
disp('busP_injection is');disp(busP_injection);
disp('busQ_injection is');disp(busQ_injection);

clear Ik In SL SLT Skn Snk
clear fff ttt
end
Power_flow=[Pabs(Pabs~=0);Qabs(Qabs~=0)];
Total_IC=sumIC;
```

A-6 Multi-Carrier Energy System: Network Data

Electricity Network Bus Data															
No	Flag	Vm	Va	PD	QD	PG	QG	Vm_min	Vm_max	Va_min	Va_max	PG_min	PG_max	QG_min	QG_max
1	0	1	0	22.75	7.49	0	0	0.94	1.06	-360	360	0	0	0	0
2	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0
3	0	1	0	28.4	8.2	0	0	0.94	1.06	-360	360	0	0	0	0
4	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0
5	0	1	0	-1.162	0	0	0	0.94	1.06	-360	360	0	0	0	0
6	0	1	0	12.73	10.22	0	0	0.94	1.06	-360	360	0	0	0	0
7	0	1	0	24.5	4.9	0	0	0.94	1.06	-360	360	0	0	0	0
8	1	1.06	0	0	0	0	0	1.06	1.06	-360	360	0	200	-200	200
9	0	1	0	12	3.5	0	0	0.94	1.06	-360	360	0	0	0	0
10	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0
11	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0
12	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0
13	0	1	0	3.44	0.96	0	0	0.94	1.06	-360	360	0	0	0	0
14	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0
15	0	1	0	0	0	0	0	0.94	1.06	-360	360	0	0	0	0

Flag=0, PQ bus; Flag=2, PV bus; Flat=1, Slack Bus

Electricity Network Line Data															
No	F	T	R	X	C_total	P_min	P_max	Tap	Shift	Status	P_old	GR	AV	DR	LS
1	2	8	0.0128	0.0131	0	-29	29	1	0	1	11.52	0.016	1001401	0.069	80
2	4	8	0.03	0.071	0	-32	32	1	0	1	20.62	0.016	1845674	0.069	80
3	6	8	0.027	0.068	0	-32	32	1	0	1	20.98	0.016	1482909	0.069	80
4	6	4	0.002	0.004	0	-36	36	1	0	1	8.11	0.016	324708	0.069	80
5	8	2	0.01285	0.01329	0	-29	29	1	0	1	11.39	0.016	1006791	0.069	80
6	8	10	0.03256	0.08945	0.008	-32	32	1	0	1	6.11	0.016	1748654	0.069	80
7	8	12	0.0493	0.09364	0.03106	-21	21	1	0	1	5.94	0.016	2162542	0.069	80
8	12	11	0.00328	0.00429	0.01712	-32	32	1	0	1	5.92	0.016	446882	0.069	80
9	14	8	0.0332	0.0709	0	-34	34	1	0	1	1.72	0.016	597966	0.069	80
10	15	8	0.0332	0.0709	0	-34	34	1	0	1	1.72	0.016	1165715	0.069	80
11	7	5	0.02362	0.04986	0.00562	-31	31	1	0	1	1.16	0.016	1178324	0.069	80
12	2	1	0.04486	0.8473	0	-23	23	1	0	1	11.44	0.016	437646	0.069	80
13	2	1	0.04539	0.8473	0	-23	23	1	0	1	11.44	0.016	437646	0.069	80
14	4	3	0.04204	0.787	0	-32	32	1	0	1	14.38	0.016	437646	0.069	80
15	4	3	0.04224	0.797	0	-32	32	1	0	1	14.2	0.016	437646	0.069	80
16	8	7	0.03066	0.58	0	-25	25	1	0	1	12.25	0.016	437646	0.069	80
17	8	7	0.02984	0.63	0	-25	25	1	0	1	11.24	0.016	437646	0.069	80
18	10	9	0.01836	0.7998	0	-32	32	1	0	1	6.09	0.016	437646	0.069	80
19	11	9	0.0179	0.7998	0	-32	32	1	0	1	5.92	0.016	437646	0.069	80
20	14	13	0.02548	0.79634	0	-40	40	1	0	1	1.72	0.016	437646	0.069	80
21	15	13	0.02563	0.79784	0	-40	40	1	0	1	1.72	0.016	437646	0.069	80

Gas Network Node Data						
No	Flag	P	QDm^3/s	QGm^3/s	QG_min	QG_max
1	0	4307	1.047	0	0	0
2	0	4392	0.626	0	0	0
3	0	4714	0.622	0	0	0
4	1	5000	0	0	0	20
5	0	4750	0.261	0	0	0
6	0	4588	0.28	0	0	0
7	0	4572	0.237	0	0	0
8	0	4522	0.841	0	0	0
9	0	4618	0.441	0	0	0
10	0	4522	0.965	0	0	0
11	0	4626	0.287	0	0	0
12	0	4961	0.551	0	0	0

Flat=0, Demand Node; Flag=2, Demand-Pressure Node; Flag=1, Reference Node

Gas Network Pipeline Data																	
No	F	T	E	Tb	Pb	G	Tf	L	Z	D	Thick	P_min	P_max	Q_old	GR	DR	LS
1	4	5	0.92	15	101	0.6	20	14.2	0.9	150	6	5001	3000	1.906	0.016	0.069	80
2	5	6	0.92	15	101	0.6	20	17.4	0.9	150	6	5000	3000	1.358	0.016	0.069	80
3	5	11	0.92	15	101	0.6	20	9.3	0.9	80	4	5000	3000	0.287	0.016	0.069	80
4	6	8	0.92	15	101	0.6	20	18	0.9	150	6	5000	3000	0.841	0.016	0.069	80
5	6	7	0.92	15	101	0.6	20	1.7	0.9	80	4	5000	3000	0.237	0.016	0.069	80
6	4	12	0.92	15	101	0.6	20	27	0.9	150	6	5000	3000	0.551	0.016	0.069	80
7	4	3	0.92	15	101	0.6	20	4.3	0.9	150	6	5000	3000	3.701	0.016	0.069	80
8	3	2	0.92	15	101	0.6	20	22.2	0.9	150	6	5000	3000	1.673	0.016	0.069	80
9	2	1	0.92	15	101	0.6	20	14.3	0.9	150	6	5000	3000	1.047	0.016	0.069	80
10	3	9	0.92	15	101	0.6	20	9.6	0.9	150	6	5000	3000	1.406	0.016	0.069	80
11	9	10	0.92	15	101	0.6	20	20	0.9	150	6	5000	3000	0.965	0.016	0.069	80

A-7 MATLAB Code: Gas Network Formulation

```
global branchP_in branchP_out
%   Read branch data
branchNumber=length(branchData(:,1));
branchF=branchData(:,2);
branchT=branchData(:,3);
branchE=branchData(:,4);
branchTb=branchData(:,5);
branchPb=branchData(:,6);
branchG=branchData(:,7);
branchTf=branchData(:,8);
branchL=branchData(:,9);
branchZ=branchData(:,10);
branchD=branchData(:,11);
branchThick=abs(branchData(:,12));
brancha=3.7435*10^(-3).*branchE.*((273+branchTb)./(branchPb)).*((branchD-
2*branchThick).^(2.667))./((branchG.*(branchTf+273).*branchL.*branchZ).^0.5
);  %Coefficient a
%   Read node data
nodeNumber=length(nodeData(:,1));
nodeType=nodeData(:,2);
nodeP=nodeData(:,3);
nodeQD_old=nodeData(:,4);
nodeQD_add=nodeData(:,8);
HtER=2;
Efficiency=0.72;
Heat_Value=40; %40MJ/m^3
nodeQD_add(AtCHP)=(y+y*HtER)/Efficiency/Heat_Value;
nodeQD=nodeQD_old+nodeQD_add;
nodeQG=nodeData(:,5);
%   This section is the gas flow solution by Newton-Raphson method
MatrixRefAt=zeros(1,nodeNumber);
MatrixNoRefAt=zeros(1,nodeNumber);
MatrixNoRefQPAt=zeros(1,nodeNumber);
for for_n=1:nodeNumber
    if nodeType(for_n) == 1
        MatrixRefAt(for_n)=1;
    else
    end
    if nodeType(for_n) == 2
        MatrixNoRefAt(for_n)=1;
    else
    end
    if nodeType(for_n) == 0 || nodeType(for_n)==3
        MatrixNoRefAt(for_n)=1;
        MatrixNoRefQPAt(for_n)=1;
    else
    end
end
disp('MatrixRefAt is'); disp(MatrixRefAt);  %MatrixRefAt is matrix with
element=1 when a Ref node occours
disp('MatrixNoRefAt is'); disp(MatrixNoRefAt);  %MatrixNoRefAt is matrix
with element=1 when a Non-Ref node occours
disp('MatrixNoRefQPAt is'); disp(MatrixNoRefQPAt);  %MatrixNoRefQPAt is
matrix with element=1 when a Non-Ref or a Non-QP node occours
% Start of iterations
g_accuracy = 0.01;
g_maxiter = 20000;
g_maxerror = 1;
```

```
g_converge=1;
g_iter = 0;
x=nodeP;
disp('x is'); disp(x);
nodeQD_sch=nodeQD;
nodeQG_sch=nodeQG;
if_n=0;
for for_n=1:nodeNumber
    if_n=if_n+1;
    if MatrixNoRefQPAt(for_n)==0
        nodeQD_sch(if_n)=[];
        nodeQG_sch(if_n)=[];
        if_n=if_n-1;
    end
end
disp('nodeQD_sch is'); disp(nodeQD_sch);
disp('nodeQG_sch is'); disp(nodeQG_sch);
fx1=zeros(nodeNumber,1);
fx2=zeros(branchNumber,1);
fx3=zeros(branchNumber,1);
fx4=zeros(branchNumber,1);
fx5=zeros(nodeNumber,1);
g_fx=zeros(nodeNumber,1);
jx1=zeros(branchNumber,1);
jx2=zeros(nodeNumber,nodeNumber);
jx=zeros(nodeNumber,nodeNumber);
while g_maxerror >= g_accuracy && g_iter <= g_maxiter
    g_iter = g_iter+1;
    %calculte fx
    for for_m=1:branchNumber
        for for_n=1:nodeNumber
            fx1(for_n)=A_T(for_m,for_n)*((x(for_n)).^2);
        end
        fx2(for_m)=sqrt((sum(fx1)));
        fx3(for_m)=brancha(for_m).*fx2(for_m);
    end
    for for_n=1:nodeNumber
        for for_m=1:branchNumber
            fx4(for_m)=A(for_n,for_m)*fx3(for_m);
        end
        fx5(for_n)=sum(fx4);
        g_fx(for_n)=fx5(for_n)/3600/24;
    end
    disp('fx is'); disp(g_fx);
    g_Fx=g_fx;
    if_n=0;
    for for_n=1:nodeNumber
        if_n=if_n+1;
        if MatrixNoRefQPAt(for_n)==0
            g_Fx(if_n)=[];
            if_n=if_n-1;
        end
    end
    disp('fx is'); disp(g_Fx);
    %calculate DC
    g_DC=nodeQG_sch-nodeQD_sch-g_Fx;
    disp('DC is'); disp(g_DC);
    %calculate J
    for for_n=1:nodeNumber
        for for_nn=1:nodeNumber
            for for_m=1:branchNumber
```

```
jx1(for_m)=A(for_n,for_m)*(brancha(for_m)*(A_T(for_m,for_nn)*nodeP(for_nn))
)/fx3(for_m);
            end
            jx2(for_n,for_nn)=sum(jx1);
            jx(for_n,for_nn)=jx2(for_n,for_nn);
        end
    end
    disp('jx is'); disp(jx);
    if_n=0;
    g_J=jx;
    for for_n=1:nodeNumber
        if_n=if_n+1;
        if MatrixNoRefQPAt(for_n)==0
            g_J(if_n,:)=[];
            g_J(:,if_n)=[];
            if_n=if_n-1;
        end
    end
    disp('J is'); disp(g_J);
    %calculate Dx
    g_Dx=g_J\g_DC;
    disp('Dx is'); disp(g_Dx);
    g_dx=g_Dx;
    if_n=0;
    for for_n=1:nodeNumber
        if_n=if_n+1;
        if MatrixNoRefQPAt(for_n)==0
            g_dx=[g_dx(1:for_n-1,:);0;g_dx(for_n:end,:)];
            if_n=if_n+1;
        end
    end
    disp('dx is'); disp(g_dx);
    %calculate x
    x=x+g_dx;
    g_maxerror=max(abs(g_DC));
    disp('maxerror is'); disp(g_maxerror);
    if g_iter == g_maxiter && g_maxerror > g_accuracy
        fprintf('\nWARNING: Iterative solution did not converged after ')
        fprintf('%g', g_iter)
        fprintf(' iterations.\n\n')
        fprintf('Press Enter to terminate the iterations and print the
results \n')
        g_converge = 0;
        pause
    else
    end
end
```

Publications

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Hantao Wang, Chenghong Gu , Furong Li and Xin Zhang Optimal "CHP Planning in Integrated Energy Systems considering Use-of-System Charge," *IEEE Transactions on Power System*, 2018, under review.

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